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Proceedings of the
GEOLOGISTS' ASSOCIATION

The Carboniferous Volcanic Rocks of the Langholm District

by ROBERT BRIAN ELLIOTT

Received 19 October 1957

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1. INTRODUCTION

THE CARBONIFEROUS basaltic lavas of the Midland Valley of Scotland, made famous by the researches of Bailey, MacGregor, Tomkeieff, Tyrrell and others, are recognised as belonging to the Basalt–Trachybasalt–Trachyte suite of the continental areas. Langholm in Eskdale, although on the south side of the Southern Uplands, is within the Midland Valley petrographic province and many of its rocks are similar to those found farther north.

The town of Langholm lies at the centre of the outcrop of the basal-Carboniferous, Birrenswark, lavas which stretch from the coast of Kirkcudbright to the headwaters of the River Liddel, a distance of about forty-five miles. A few miles to the east of Langholm is an area of lavas in

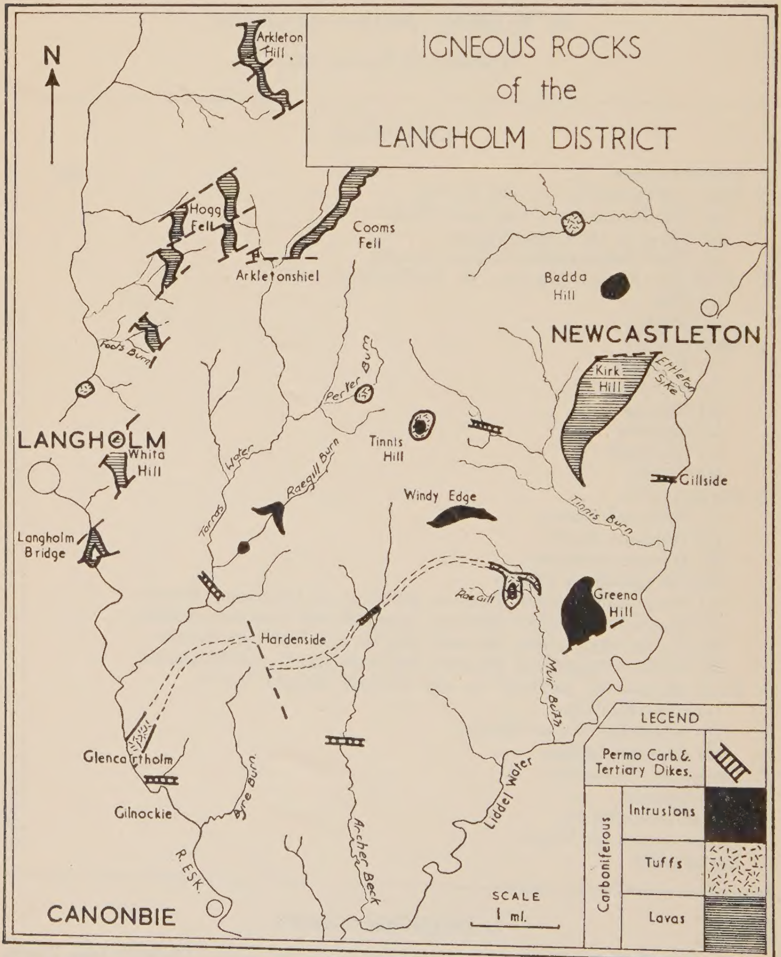


Fig. 1. Map of the igneous rocks of the Langholm district based on Geological Survey maps with modifications by the author

the Cementstones and to the south is Glencartholm, which gives its name to a group of volcanic rocks between the Fell Sandstones and the Lawston Lynn Coal Group. The district is, therefore, capable of providing a fairly complete picture of Lower Carboniferous vulcanicity in south-west Scotland (Fig. 1).

The stratigraphy and structure were described by Peach & Horne in their account of the Geology of the Canonbie Coalfield (1913) and Richey & Barrett added new facts in their Wartime Memoir (1942) on the same area. The igneous rocks received passing mention from both Teall (1883) and Geikie (1897) and were briefly described by Lady M'Robert (1916) as part of a wider study of the rocks of Teviot and Liddisdale.

2. FIELD OCCURRENCE OF THE LAVAS

(a) The Birrenswark Volcanic Group

The Birrenswark lavas, at the base of the Carboniferous system, form a well-defined horizon of which the broken and faulted outcrop may be traced from Langholm towards the north-east. Their thickness varies from 45 to 250 feet, and the change in thickness often takes place in a short distance (Fig. 2). The individual flows do not appear to be extensive and can rarely be recognised from one locality to the next. In consequence it is concluded that they once formed a minor plateau composed of numerous small interdigitating flows. Each flow has a central portion of massive basalt, a thin slaggy base and at the top a vesicular layer whose presence makes the counting of flows possible.

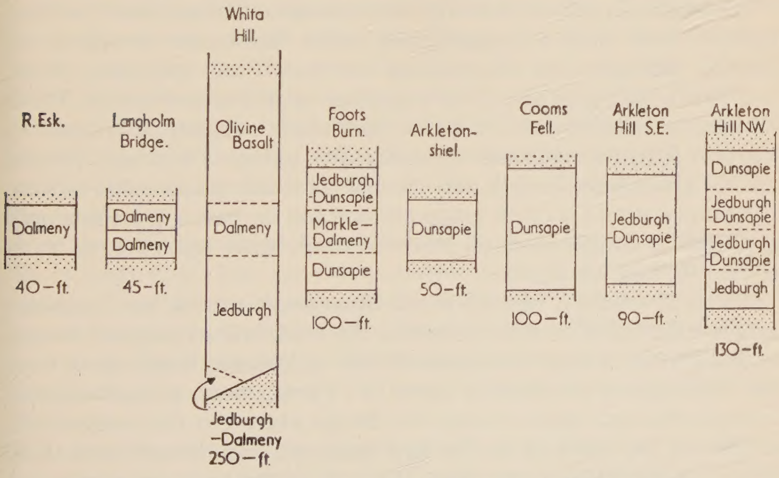


Fig. 2. Thicknesses and lava types in the Birrenswark Volcanic Group

The lavas are all olivine basalts, mostly the microporphyritic Jedburgh, Dalmeny or Jedburgh–Dalmeny types but with macroporphyritic types, e.g. Dunsapie and Dunsapie–Markle, well represented. In both thicknesses and rock types the igneous rocks of Langholm correspond very closely with those occurring to the south-west, between Annandale and the River Esk (Pallister, 1952). There is no reasonable doubt that they are all part of the same lava plateau. In terms of basaltic type, each flow is normally uniform across its thickness and with one possible exception contrasting rock types are invariably separated by a vesicular layer. It is less certain that they maintain their identity in a horizontal direction; there may be a slight change in the phenocryst distribution. Most of the lavas are vesicular to some degree but the property is usually well marked only in the upper layers. In general the vesicles are small and round, lined with chlorite and filled with calcite so that they appear green in the hand-specimen when unbroken and white when cracked across.

Xenoliths are not common and where they have been observed show only slight alteration. On the water-polished slabs below Langholm Bridge are sections of cognate xenoliths of more vesicular lava enclosed in the compact rock. These may be lava bombs or fragments of the crust of the flow that were pulled down into the lower part of the flow and rounded.

The basalts are almost invariably decomposed and in the hand-specimen many of them have a purplish-green colour due to the abundance of chlorite, iddingsite and disseminated iron-ores. Fresh specimens of the lava have a dark grey colour but a greenish tinge is seldom absent. Fresh olivine is extremely rare in the rocks; fresh augite is slightly more common and only felspar is comparatively unchanged. Calcite is invariably present and the groundmass is dark with the finely divided opaque oxide of iron.

Nowhere is the top of the group exposed and the base is to be seen only at Langholm Bridge where the lavas rest conformably upon the red marls of the Old Red Sandstone.

The most southerly outcrop of the Birrenswark lavas in the Langholm area is in the bed of the River Esk about 500 yards below Langholm Bridge, at Sowie's Pot. A single homogeneous flow of Dalmeny basalt about forty feet thick dips to the south at about 15°. Farther north a small anticline brings in the lavas again at Langholm Bridge where they rest conformably on the red silty marls of the Old Red Sandstone and dip north at a small angle. The visible lava is made up of two flows, the lower one twenty-five feet thick and the upper seventeen feet thick with a slaggy layer in between them. Both are Dalmeny basalts although the upper one becomes slightly more felspathic than normal in patches in its upper portions.

About a mile north-east of Langholm Bridge, on Whita Hill, the lavas attain a thickness of 250 feet. There is no continuous section but frequent scoriaceous bands and variations in lava type indicate that several flows are present. The lowest lava is a transition Jedburgh–Dalmeny type forming a thin flow of limited extent. It is overlain by a vesicular Jedburgh basalt of which the upper part has many amygdales, where the sequence of deposition of the late magmatic minerals may be established.

Above the Jedburgh basalt is a more basic flow of very fine grained Dalmeny basalt, while still higher in the sequence the basalts are weathered to such a degree that their types cannot be determined. The junction with the overlying Whita sandstone is not seen.

To the north of Langholm the Birrenswark lavas outcrop again in Foots Burn. The junction with the sediments is not seen and the lowest lava visible is a decomposed Dunsapie basalt conspicuous by the size of its olivine and plagioclase phenocrysts which may reach five millimetres in length. The overlying rock is relatively richer in felspars. It is still a Dunsapie basalt, however, with affinities with the Markle type. It is not clear whether these two rocks are separate flows or parts of the same flow in which there is a downward concentration of olivine. There is no sign of any slaggy intervening layer but exposures are not good and the fact that it is not to be seen does not mean that it does not exist. A band of scoriaceous lava separates the lower rocks from a flow of finer Markle–Dalmeny basalt.

The macroporphyritic basalts are overlain in turn by a fresh, dark-grey Jedburgh–Dalmeny basalt with microphenocrysts of the three common porphyritic elements. The succeeding lavas are highly weathered basalts which bring the total thickness of volcanic rocks up to about 100 feet.

North of Foots Burn the next important outcrop of the lava plateau is on Arkleton Hill where the rocks ring the upper south-west part of the fell and give rise to a discontinuous line of crags, diminishing in height towards the south-east.

At the south-east end of the lava outcrop there is no evidence of anything but a single flow. The type closely resembles the Jedburgh type with its elongate small felspar crystals. However, there are present very sporadic macrophenocrysts, two or three per hand-specimen, of olivine and felspar, as well as some larger augites which indicate that the rock has some of the characters of the Dunsapie type of basalt although these are not strongly marked.

A short distance from the south-east end of the exposure is an outcrop of vesicular lava in vertical contact with non-vesicular material. This probably represents a small subsidiary vent through which lava was poured and suggests that the formation of gases went on most actively in the volcanic throat, so that the majority of the gas was lost there and that the lava flows were, in consequence, almost non-vesicular.

Farther to the north-west, almost at the limit of the outcrop, is a prominent crag of concave shape called White Cove which gives a good section of the lavas and an accompanying agglomerate. Here four lava flows are visible and the thickness of lava is consequently greater than to the immediate south-east. The lowest three lava flows are truncated by the agglomerate and the whole overlain by the fourth flow. From the size of the fragments of the agglomerate a volcano must have been in existence nearby.

The lowest lava is a grey-green Jedburgh–Markle basalt with infrequent phenocrysts which have a maximum size of five millimetres. The second flow is a Jedburgh–Dunsapie basalt in which the phenocrysts of olivine and augite occur in a matrix of long fluxionally arranged felspars. The third flow is a Jedburgh–Dalmeny type and the uppermost flow is a strikingly porphyritic Dunsapie basalt in which all types of phenocrysts show seriate porphyritic arrangement, with maximum diameters as follows: felspar, five; augite, one and a half; and olivine, two millimetres respectively. This fourth flow is probably the 'large intrusion . . . of Dunsapie Basalt' of Lady M'Robert (1916).

From the mineralogical composition it is most likely that the third basalt of White Cove is the one to be correlated with that farther to the south-east at Under Nick.

Lavas of the Birrenswark horizon occur in the valley of the Tarras Water, north of Arkletonshiel, mainly on the east side of the valley and continuing towards the north-east as described by Lady M'Robert (1916). At Arkletonshiel itself the lavas occur on both sides of the valley, the outcrop being duplicated on the western side due to strike faulting. On Cooms Fell, on the eastern side of the valley, occurs a unique variety of Dunsapie basalt in a single flow almost 100 feet thick. The feature imparting this singularity is the presence of rhombic pyroxene in large crystals, in addition to the normal augite (Plate 1 A). The rock is very fresh and black and carries conspicuous phenocrysts of felspar, olivine and pyroxene. The only other record of rhombic pyroxene in Carboniferous rocks of which I am aware is that of Lady M'Robert (1916) in an intrusive rock which occurs a short distance from Arkletonshiel and which was regarded as a vent from which some of the Birrenswark lavas were poured. The two rocks are, without doubt, closely related and may represent the same magma.

(b) Lavas in the Cementstones

The Birrenswark lavas are overlain by about 800 feet of thick sandstones, the Whita Sandstone, which is in turn overlain by another 800 feet of Cementstones. The lavas in the Cementstones occur near the top of the group and so are separated from the Birrenswark horizon by about 1400 feet of strata.

The lavas are found on Kirk Hill, south-west of Newcastleton, where they reach a thickness of over 870 feet, unless the sheet is folded, and cover a greater area than that covered by the entire outcrop of the Glencartholm volcanic rocks. In spite of their considerable thickness they cannot be traced very far and it appears, as Geikie (1897) thought of lavas elsewhere on this horizon, that they were the result of activity at an isolated centre with the activity restricted to a small area round the vent. They are not, however, associated with ashes and the only pyroclastic material is in patches and pockets on the surface of the lava. It would appear that these Cementstone lavas are distinguished from the normal 'puy' by the absence of tuff and instead form a connecting link between the 'plateau' and 'puy' type of activity. They resemble the former in the dominance of lava amongst the products of vulcanicity and the latter by their inability to build up a continuous sheet.

The igneous rock is exposed only at the base and top of the lava pile so that the picture is incomplete. The basal lava is a reddish decomposed Dunsapie basalt in which the phenocrysts are about two millimetres in diameter. The felspars slightly exceed this size whilst the pyroxenes are slightly smaller. On the eastern side of Kirk Hill in Ettleton Sike, the top of the lava is exposed overlain by sandy sediments. The upper basalt is a Dalmeny basalt, quite distinct from the lower one; the phenocrysts are smaller, the groundmass is coarser, the olivines are more numerous and there are fewer felspars. It is without doubt a separate flow.

(c) The Glencartholm Volcanic Group

The Cementstones in Eskdale are overlain by about 100 feet of thick sandstones, the Fell Sandstone, which is in turn overlain by a group of volcanic rocks sometimes called the Glencartholm Lavas.

The name 'lavas' is misleading because the classic section contains no lavas and is made up entirely of well-bedded tuffs, fine agglomerates and tuffaceous sediments which dip downstream at a small angle. The width of the outcrop is about a quarter of a mile so that, taking an average dip of 15°, the thickness is about 300 feet. From Glencartholm the outcrop runs to the north-east in the direction of Bruntshiel Hill and north-east of Hardenside the horizon crosses the upper reaches of the Archer Beck where there is exposed a decomposed basalt. This was originally mapped by the Geological Survey as a dyke; its field relations are quite obscure but since it lies on the line of outcrop of the Glencartholm lavas it is preferred to regard it as one of these. It is quite distinctive for this horizon being a Dunsapie basalt with large phenocrysts, some of which reach as much as two centimetres in length.

Farther still to the east in Muir Burn and Rae Gill are lava and tuffs sharply folded and overlain by Glencartholm shales. The lava, a Dalmeny basalt, which is poorly exposed in a waterfall in Rae Gill, has a distinctly bedded appearance with rusty division planes often enhanced by calcite veinlets parallel to the stratification planes of the adjacent sediments.

3. INTRUSIVE ROCKS RELATED TO VULCANICITY

Tomkeieff makes the following comment on the rocks of the Tweed Basin. 'The most striking feature of the igneous rocks of this district is the contrast between the contemporaneous extrusive rocks, usually highly altered basalts and dolerites which are often vesicular and greenish-grey in colour, and the supposedly intrusive rocks—fresh bluish-grey basalts and dolerites. The local people call the first "greenstones" and the second kind "bluestones" ' (Tomkeieff, 1945, 54). It might be expected that this criterion would also apply to similar rocks of similar age occurring a few miles to the south of the Tweed Basin and where examples of both intrusions and lavas are to be found. The Birrenswark lavas are all greenstones and the neck of Tinnis Hill, an undeniable intrusion, is a bluestone. The features of the undoubted lavas, apart from colour, are as follows: they are usually margined by an upper vesicular zone and a lower highly altered layer and they contain scattered vesicles throughout even though these may be sometimes infrequent; they often contain patches of agglomeratic material, particularly along their soles and on their tops; their olivines alter to iddingsite; and they have a remarkable uniformity of grain size and texture from margin to centre. In contrast the undoubted dyke rocks, the quartz-dolerites, show marginal zones much finer in grain than the central portion and have neither vesicles nor agglomeratic material. Applying the above criteria, we find that the following have chilled margins, no vesicles, and no visible agglomeratic material—the Greena Hill (Dinwoodie) basalt and the Raegill Burn rock. Both are bluestones: they are therefore regarded as intrusions. The Bedda Hill occurrence has a circular outcrop and it is almost without doubt a composite plug. One of the basalts, a Craiglockhart basalt, is a bluestone, the other, much more weathered, is a typical greenstone. The sheet on Windy Edge is non-vesicular and has serpentinised olivines. It compares closely with the Greena Hill rock and is probably a sill. The Cooms Fell rock is anomalous. It occurs on the Birrenswark horizon and is a greenstone when altered but a bluestone when perfectly fresh; it is non-vesicular but shows no chilling at its lower margin and is remarkably uniform in texture throughout .The chance of an intrusion occurring along a thin volcanic horizon seems remote and, since the basalt resembles others on the same horizon, it is regarded as a flow. In conclusion, it appears that 'greenstones' and 'bluestones' do, in the main, correspond to lavas and intrusions but there is one intrusive greenstone—a neck—and one extrusive bluestone in the area.

(a) Sills

(*i*) *Raegill Burn.* Raegill Burn is an eastern tributary of the Tarras Water which flows in a south-westerly direction. In its upper reaches, at an altitude of about 700 feet, is an exposure of grey basalt. The junction with the enclosing Cementstones is not seen but its trend is clear enough and it seems to be conformable with the strata. The sill is exposed through a vertical distance of about twenty-five feet, and, since the dip is small, the thickness is probably not much greater than this figure. The rock is a distinctive one for it is a fine uniformly grained basalt without any apparent structure. It contains no vesicles, no phenocrysts and no suggestion of slagginess; it resembles, in fact, a grey crystalline limestone and is a transition Mugearite–Jedburgh basalt. In spite of the uniformity of hand-specimens there is a change in micro-texture from trachytic near the margin to non-directive in the centre. Some distance downstream from the sill is an isolated exposure of an identical rock. It is surrounded on at least three sides by sandstone so that it is a pipe, perhaps that through which the sill was intruded.

(*ii*) *Greena Hill.* This is the 'Dinwoodie lava' of Lady M'Robert (1916) and it forms a patch, roughly half a mile in diameter, resting on Fell Sandstone and capping Greena Hill. Neither the base nor the top of the sheet is exposed but the lowest chilled rock is 200 feet below the summit of the hill and all exposures above this are in igneous rock. It would appear that the thickness of the sheet is of the order of 200 feet.

The margin is chilled and is a fine, homogeneous and almost non-porphyritic greenish-grey Jedburgh basalt with pronounced platy jointing and a thin brown weathered skin.

The coarser rock, making up the bulk of the sheet, is also a Jedburgh basalt. It is decidedly doleritic in appearance being of dark grey colour and with many slender felspars about two millimetres in length, which in thin section display a trachy-ophitic relationship with augite.

(*iii*) *Windy Edge.* About three miles north-west of Kershopefoot is a low ridge which is now the site of an extensive plantation. All exposures near the crest of the ridge are of igneous rock while lower exposures are in the Fell Sandstone. The field relations are obscure for it is not at all clear whether the igneous sheet lies above or below the nearby sandstones which dip irregularly and must be quite sharply folded. All that can be said with certainty is that the igneous horizon is about that of the Fell Sandstone. The basalt is of Dalmeny type and in hand-specimen is dark and grey without visible phenocrysts. The groundmass felspars are long and distinct but olivine crystals are seen only with difficulty. What is interpreted as the upper chilled margin is fine in grain, without visible phenocrysts and intensely weathered.

(b) Necks

(*i*) *Tinnis Hill*. Tinnis Hill is the most prominent hill in the neighbourhood and its smooth conical form stands above the general level of the surrounding moors. It has been described as a neck of fine-grained and fairly uniform tuff pierced by a very fine non-porphyritic basalt (M'Robert, 1916). This is an over-simplified picture, for present exposures are in agglomerate with fragments up to three inches in diameter, as well as in two different types of basalt. Exposures are rather temporary affairs on hills like Tinnis and at the moment the fine tuff is not exposed. The neck is clearly a composite one in the sense of being made up of more than one type of ash as well as more than one type of igneous rock. The summit rock is a very fresh Dalmeny basalt with phenocrysts of olivine along with a few augites in a rather felspathic base. This is probably the rock which was described as 'resembling the Jedburgh type of basalt except for its preponderance of augite phenocrysts which indicate a passage to the Dalmeny' (M'Robert, 1916). The basalt exposed on the eastern side of the hill is much finer in grain, is dark grey in colour and contains numerous scattered microphenocrysts of olivine, with a few augites and felspars, in a very fine base. It is also of Dalmeny type and may either be a separate intrusion or the margin of the summit rock. It has been suggested previously (M'Robert, 1916) that Tinnis Hill might mark the site of one of the volcanoes from which the Glencartholm lavas were poured, a supposition based mainly on the resemblance between the Tinnis Hill rock and that of Greena Hill. I regard the latter as a sill and not a flow and in any case the resemblance is not particularly close. Tinnis Hill neck cuts the Cementstones, so it might equally well be the feeder for any of the lava flows in the Cementstones or higher beds.

(*ii*) *Bedda Hill*. Bedda Hill, two miles west of Newcastleton on the old Langholm Moor road, is composed of a patch of igneous rock, has a strikingly circular outcrop, and is almost certainly a volcanic neck. The neck is a composite one composed of a deeply weathered Jedburgh basalt and a fresh Craiglockhart basalt. The former makes up the greater part of the hill and the latter is only found in one small cutting. The Craiglockhart basalt is very dark grey in colour and contains numerous large augite crystals. Some of these reach one centimetre in length and the average size is about three millimetres. Olivines, which are also numerous, are somewhat smaller and have an average diameter of over two millimetres. The ratio of augite to olivine phenocrysts is about 3 to 1.

4. MINERALOGY

The lavas are all either basalts or trachybasalts and their mineralogy is simple; they consist of felspar, pyroxene and olivine with late-stage minerals.

(a) Felspars

The felspars do not vary greatly in composition in the basalts and nearly all fall within the labradorite range. The more calcic felspars are those of the Dunsapie basalts which average $Ab_{33}.An_{67}$; the Dalmeny basalts have felspars near the composition $Ab_{41}.An_{59}$ and the Jedburgh basalts average about $Ab_{47}.An_{53}$. The Jedburgh basalts show more variation than the others and their felspars may lie between $Ab_{45}.An_{55}$ and $Ab_{57}.An_{43}$.

As a rule the felspars are not markedly zoned although the large ones frequently have rims of different composition. In any rock the felspars are not all of exactly the same composition; the variation has not been specifically measured but a comparison of determinations from refractive indices, statistical methods and selected sections shows that it does exist.

Felspars of the rocks transitional between Mugearite and Jedburgh basalt have a more sodic composition as well as a more extended range from $Ab_{52}.An_{48}$ to $Ab_{80}.An_{20}$. The majority are about $Ab_{60}.An_{40}$ with the sporadic phenocrysts more calcic and the late interstitial felspars of the oligoclase variety. Most of the felspars are elongate, especially those of the groundmass where the length/breadth ratio is about 5 or 6/1. Only the large phenocrysts of the Dunsapie basalts have a form approaching equidimensional.

(b) Pyroxenes

The normal pyroxene of the basalts is pale brown and non-pleochroic augite. It is not usually fresh but is altered to chlorite or other late-stage minerals. Of the fresh augites, two have been measured fully. The first, from a Jedburgh basalt, had $\gamma = 1.716 \pm .001$, $\alpha = 1.693 \pm .001$ and $+ 2V = 53°$; the other in a Dunsapie basalt had $\gamma = 1.718 \pm .002$, $\alpha = 1.692 \pm .002$ and $+ 2V = 50°$. One of these is a phenocryst, the other part of an ophitic intergrowth and since the lowest value of 2V recorded for any of the monoclinic pyroxenes in any of the rocks was 48°, which is still within the augite range (Hess, 1941, 1949), there is no reason to suspect any great variation in the composition of the monoclinic pyroxene.

Orthorhombic pyroxene occurs in one Dunsapie basalt on Cooms Fell as large crystals in clusters rimmed by augite (Plate 1 A). It has the following optical properties:

$$\gamma = 1.691 \pm .001 \text{ and } \alpha = 1.679 \pm .001 \quad - 2V = 76°$$

It is colourless in thin section but pleochroic in thicker fragments with Z = pale green and X = brownish-red. Its Enstatite/Ferrosillite ratio from this data is 82/18.

(c) Olivine

Fresh olivine is present in only a few lavas but its pseudomorphs are very common. Only one lava has olivine fresh enough to be separated; this had $\beta = 1.690 \pm .005$ and the Forsterite/Fayalite ratio is therefore 80/20, almost the same as that of the orthorhombic pyroxene. It alters to either iddingsite or serpentine often without loss of crystal form so that its former presence is seldom in doubt.

(d) Chlorite

Chlorite occurs in a wide variety of forms; replacing augite and olivine as well as in irregular patches in the groundmass and as vescicle filling. All measured chlorites, with the exception of some vermicular material filling the core of decomposed olivines, have $\beta = 1.605 \pm .002$, 2V is small and negative and the birefringence is low. It is pleochroic from pale green to almost colourless and is probably delessite. In the weathered skin of rocks the chlorite has become brown and highly birefringent, from which it is clear that the green chlorite is not a product of normal weathering.

(e) Iddingsite

Most olivine pseudomorphs are composite but iddingsite makes up a large part of many of them. It has a high variable R.I., above 1.76, is dark red in colour and has $- 2V = 40°$. The cleavage is perfect and extinction straight. In many sections it is practically opaque and in others has highly variegated colours. The polarisation colours are second and third order but are heavily masked by the deep body colour.

In conjunction with iddingsite and often occurring at the centre of pseudomorphs is a yellow mica-like mineral, pleochroic in shades of yellow and orange, with $\beta = 1.60$, low birefringence and 2V sensibly zero. It is present in large quantities as a major constituent of the olivine pseudomorphs, and is here referred to as bowlingite, although this identification is not certain.

(f) Calcite

Calcite is present in all the lavas in a large variety of forms, from thin veinlets in the felspars to large plates in the groundmass. Very rarely there is also dolomite, as in the agglomerate patches in the lava at Langholm Bridge.

5. PETROGRAPHY

(a) Jedburgh Basalts

These occur on Whita Hill, Arkleton Hill, Bedda Hill and Greena Hill (Fig. 1). They are fine and microporphyritic, and typically they carry small elongate phenocrysts of plagioclase. These have a composition about $Ab_{47}.An_{53}$; their length/breadth ratio is about 6/1 and they are usually flow orientated. Pseudomorphs after olivine are plentiful, but are small and seldom attain 1 mm. in size. The groundmass is largely composed of felspar of which the crystals have an average length of about 0.1 mm. Flow alignment is common and flow-aligned felspars sometimes run through larger plates of augite (trachy-ophitic texture). When the pyroxene is fresh the texture is normally either intergranular or ophitic, but when the rock is altered the groundmass is a plexus of felspars with much finely disseminated and irregular chlorite, calcite and iron ores. There is often a thin weathered skin and a well-marked platy jointing.

(b) Dalmeny Basalts

There are two varieties: that in which the phenocrysts are small and insignificant and the felspars are long, as at Langholm Bridge, Whita Hill, Windy Edge and Rae Gill, and the other which has a more definite porphyritic texture as at Tinnis Hill and Ettleton Sike.

In the former the olivines are only slightly larger than the felspars and are often about 0.5 mm. in diameter. They are abundant and are distinctive in the hand-specimen on account of their strikingly coloured pseudomorphs. Very sporadic macrophenocrysts may occur, up to four millimetres long, as at Langholm Bridge. The felspars of the groundmass are long, up to 0.4 mm., and in those Dalmeny basalts where olivines are most numerous the porphyritic texture is almost absent. An average size for the felspars is about 0.25 mm. Augites occur as very small granules aggregated between the felspar laths in an intergranular relationship. It is, however, unusual to find augite fresh, and its place is normally taken by a mixture of calcite and chlorite.

In the altered basalts there is no trace of any mesostasis, but in the fresh rock of Windy Edge there is an immaturely crystallised residuum reminiscent of the Sarkshiels basalt (MacGregor, *in* Barrett & Richey, 1945). This appears as dusty or, less commonly, clear patches with fine thread-like crystals growing through them. Between crossed nicols the patches show low polarisation colours which extinguish unevenly. It seems probable that the residuum is largely felspathic. Also filling in the interstices in the basalt are several zeolites including natrolite and analcite. Slight flow structure is present in the groundmass felspars, but it is not marked as in the Jedburgh basalts.

The second variety of Dalmeny basalt has numerous phenocrysts of olivine, a few scattered phenocrysts of augite and very occasional crystals of felspar which reach phenocryst dimensions. The olivines are fresh and serially porphyritic from a maximum of 1.0 mm. diameter to a size commensurate with that of the granules of augite in the groundmass. The larger augites reach 0.5 mm. diameter but are much less abundant than the olivines. The groundmass is composed of augite, rather long felspars, magnetite with subordinate amounts of the brown hornblendic mineral of the mugearites (Flett, 1908), some chlorite, apatite and very small amounts of zeolites and hemi-crystalline felspathic material. The distribution of the groundmass constituents is not even, for the augite granules often occur in clusters sometimes round an olivine phenocryst.

(c) Dunsapie Basalts

These occur in Foots Burn, Arkleton Hill, Arkletonshiel, Cooms Fell, Hardenside and Kirk Hill. They are macroporphyritic basalts with phenocrysts of olivine, augite and felspar. Felspars are the most abundant phenocrysts, augites are slightly less numerous and olivines are comparatively infrequent. An average of the percentages of the phenocrysts by volume is felspar 47%, augite 44% and olivine 9%.

The felspars form the largest crystals often up to 5.0 mm. in diameter and, in the case of the Hardenside rocks, even reaching 2.0 cm. The olivines and augites are smaller and it is normal for only one of them to be of macrophenocryst proportions; for example the Hardenside and Cooms Fell rocks have macrophenocrysts of felspar and augite and microphenocrysts of olivine whilst the Arkleton Hill Dunsapie basalt has macrophenocrysts of felspar and olivine and microphenocrysts of augite.

The porphyritic felspars are rather more calcic than those of other basalts and their composition usually lies within the range from $Ab_{30}.An_{70}$ to $Ab_{36}.An_{64}$. The felspar laths are smaller than in the Dalmeny and Jedburgh basalts and average lengths vary from 0.015 mm. to a maximum of 0.15 mm. In some of these basalts the felspars do not have their customary form but instead are quite shapeless. The groundmass augites are short prisms and are normally replaced by alteration products. The Cooms Fell Dunsapie basalt is unique in containing orthorhombic pyroxene.

(d) Craiglockhart Basalts

Craiglockhart basalt is found only on Bedda Hill. It is characterised by the presence of a great many phenocrysts of augite and olivine and the rare occurrence of phenocrysts of felspar. The average diameter of the olivines is about 2.5 mm., that of the augites is about 3.0 mm., but some of the larger augites are as large as 1.0 cm. The olivines, many euhedral, are completely changed to a fibrous yellow-green alteration product with brilliant polarisation colours. Sometimes the fibres of this secondary mineral are parallel over the whole pseudomorph but more often they show a common orientation over a smaller area. The pyroxene crystals are almost invariably full of inclusions of the groundmass, some of them to such an extent that a mere mesh of augite remains. Yet in spite of this intense alteration, many of them show perfect euhedral form. The plagioclase phenocrysts, calcic labradorite, are very sporadic, they show good shape, and are slightly altered with the production of micaceous minerals. The groundmass is composed principally of augite, felspar and magnetite with which are associated chlorite and a base that is mostly clear and isotropic but in some places dusty and birefringent in dark colours. As in the Dalmeny basalts, the augite granules cluster together and give an unevenness to the texture. The small felspars are very variable in shape, some long and slender, others short and squat; they show little zoning and their composition is the same as that of the phenocrysts. There are also present small cracks and amygdales filled with analcite which suggests that the isotropic base may also be in part analcite.

(e) Rocks Intermediate Between Jedburgh and Dalmeny Basalts

Lavas of this type occur on Whita Hill and Arkleton Hill. They resemble the Jedburgh basalts but have only a few phenocrysts of felspar without flow arrangement. They are more felspathic than the Dalmeny basalts but resemble them in carrying numerous phenocrysts of olivine.

(f) Rocks Intermediate Between Jedburgh and Dunsapie Basalts

These occur in Foots Burn and on Arkleton Hill and differ from typical Jedburgh basalts in containing either augite microphenocrysts in addition to those of felspar and olivine or scattered macrophenocrysts of olivine and plagioclase or augite.

(g) Rocks Intermediate Between Markle and Dalmeny Basalts

One flow of this kind occurs in Foots Burn. The rock resembles the Markle basalts in the large size of its many felspar phenocrysts but contains in addition both olivine and plagioclase as microphenocrysts.

(h) Rocks Intermediate Between Jedburgh Basalt and Mugearite

Rocks of this kind occur as intrusions in Raegill Burn. The margins of the intrusions show a strong trachytic texture and the interiors have randomly orientated, irregular felspar crystals. They are dominantly felspathic, with about 60% felspar and the remainder of the rock composed of calcite, chlorite and iron ores. Small and infrequent microphenocrysts of felspar exist as well as small pseudomorphs in calcite and iron ores after some indeterminate ferromagnesian mineral. The felspars are variable in composition from $Ab_{52}.An_{48}$ to $Ab_{80}.An_{20}$, with the majority about $Ab_{60}.An_{40}$.

6. LATE MAGMATIC ACTIVITY IN THE OLIVINE BASALT LAVAS

The lavas, like those of Birrenswark, farther to the south-west (Pallister, 1952), are seldom fresh but are changed to such an extent that olivine and augite are seldom preserved. Many states of alteration exist and, in a general way, successive stages can be recognised. This in its turn allows conclusions to be drawn about the time and conditions of the alteration.

(a) Chloritisation

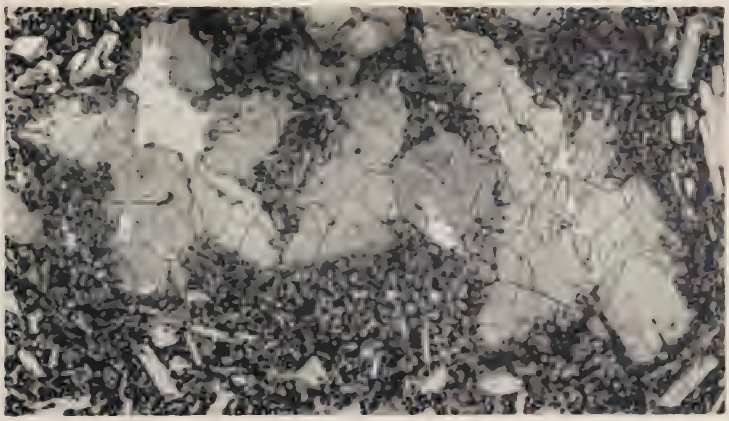
The most widespread late magmatic mineral is chlorite which is present in all but the freshest rocks. This mineral is abundant in the vesicles of the basalts on Whita Hill where amygdales are beautifully developed and show the following sequence: chlorite, calcite, quartz, along with sporadic siderite which may occur before or after the chlorite (cf. Pallister, 1952, fig. 2). Most of the vesicles have a thin skin of radially fibrous chlorite round their margins and are filled in mainly with calcite (Plate 1 B). Quartz is not found in all of them. As a rule the majority are roughly spherical in shape and have unbroken rims. Not all of them are round, however, for some of the vesicles have collapsed, their chlorite linings have been broken into fragments and now appear as short lengths with transverse fibres. Mobile lava has been intruded into the gas cavity where it has consolidated as normal, though highly carbonatised, basalt and, in the reduced gas cavity, calcite has also crystallised (Plate 1 B). Apart from the occasional collapsed vesicle, the basalts show no other signs of disturbance and there is no suggestion of shearing. In the absence of tectonic forces to produce the collapse and due to the entry of a lava tongue into the vesicle it is concluded that the fracturing was produced during flow. If this is so then it follows that the chlorite rims were in existence before the lava stopped moving, and because it appears unlikely that there was sufficient time for the operation of extraneous solutions it is concluded that the chlorite was formed by late magmatic fluids of the magma and therefore that it is deuteric.

It would appear that, at the time of their fracture, the vesicles contained highly carbonated water which was released when the chlorite lining broke and which altered the inflowing basalt liquid as well as some of the surrounding rock.

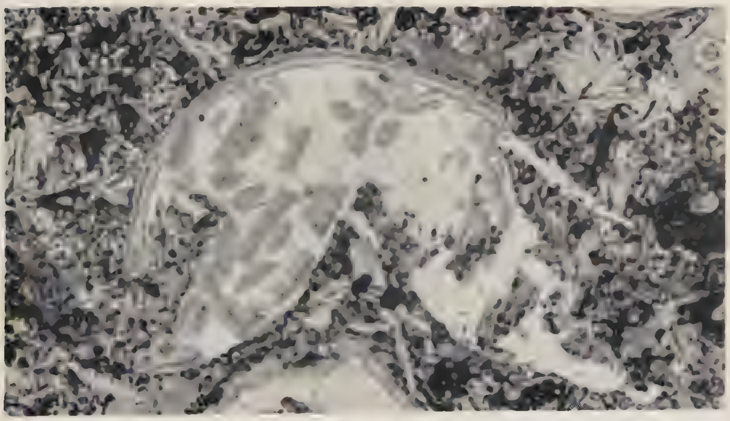
Most of the chlorite does not occur in vesicles but as an important mineral in the fabric of the rock itself. Where the rocks are little altered, like those in the upper part of the valley of the Tarras Water, the augite phenocrysts are slightly chloritised and the small groundmass augites are completely converted. In more altered rocks, as in those of Ettleton Sike and Arkleton Hill, both phenocrysts and groundmass granules have been changed. The chlorite of the phenocrysts occurs as a number of flakes aggregated into numerous sheaves and that of the groundmass as small patches of sub-parallel flakes.

While much of the chlorite of the groundmass can be referred to replaced augite some of the patches in the more heavily chloritised rocks have such a size and shape that they can only be either irregular replacements or late magmatic deposits in cavities.

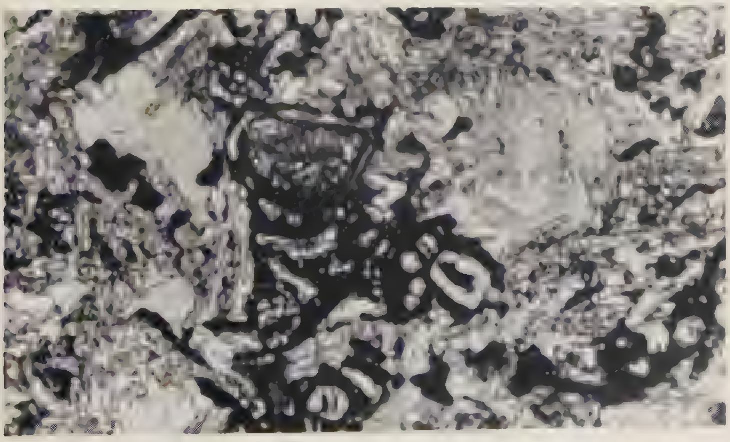
The basalts of the River Esk, south of Langholm, show this stage of alteration (Plate 1 C). In them the chlorite occurs in large patches, or



A



B



C

[*To face p.* 16

'lakes', of irregular shape composed of a number of small roughly equidimensional crystals margined by a zone of fibrous chlorite with fibres perpendicular to the margins of the patch. The disposition of the fibres suggests a cavity-filling process analogous to that which filled the vesicles and gave rise to a similar structure. That the 'lakes' are not cavity fillings, however, is evident both from the occasional presence inside them of felspar laths completely surrounded by chlorite and also by the presence on their margins of chlorite pseudomorphs after felspar. These pseudomorphs are elongate, tabular in outline, composed of fibrous green chlorite in which remnants of the plagioclase twinning is sometimes still visible. The chlorite patches are, therefore, replacement patches which must have been formed at the expense of all other previously formed constituents.

Chloritisation is, therefore, a process which in its early stages attacks ferromagnesian minerals and in its later stages all the minerals of the groundmass.

The chlorite of vesicles and 'lakes' is similar in optical properties, it is all delessite of R.I. = 1.60, 2V small and optically negative. It therefore all formed under approximately the same conditions of pressure and temperature. Since the chlorite of the vesicles is deuteric that of the 'lakes' is most probably deuteric also.

Near to the undoubtedly weathered surface of the basalt, the pale green chlorite loses its green colour, becomes greenish-brown and at the same time acquires a higher birefringence. In the weathered skin itself the chlorite is stained to opacity by oxides of iron.

(b) Alteration of the Olivines

The most striking of the alteration products of the primary minerals is the change of olivine into the mineral called 'iddingsite' by many other workers. A statement such as 'the olivines show the "iddingsite" mode of decomposition' is frequently encountered in the literature of the Carboniferous basalts (M'Robert, 1916; MacGregor, 1928), and the fact that the name iddingsite is placed in inverted commas suggests that a writer is not entirely happy about the identification of this mineral, but is following accepted practice in so naming the deep red olivine pseudomorph.

The careful study made by Ross & Shannon (1925) shows that the properties of iddingsite are not constant: the value for β ranges from 1.65 to 1.846, the optic axial angle from 25° to 90°, while the optic sign may be positive or negative. In the face of this variability of properties reticence about identification is understandable and the present author proposes to use the term 'iddingsite' as if it was in inverted commas. At the same time it is hoped to establish that the yellow and red decomposition products of the Langholm rocks are not all composed of the same mineral but of two, quite different, minerals.

In the freshest rocks, for example those on Cooms Fell and Tinnis Hill, olivine is accompanied by pale green decomposition products of the type which are usually closely called 'serpentine' and nowhere in the district is fresh olivine associated with 'iddingsite'. The replacement of olivine by 'iddingsite' is always complete so that there is no information about the early change. That it does take place at an early stage, however, is shown by the association of iddingsite with only partly altered augite, as at Arkletonshiel, where a Dunsapie basalt with extremely fresh felspar and augites partially changed to calcite and chlorite carries numerous completely altered pseudomorphs of olivine. In a related type of rock, the Dunsapie basalt on Arkleton Fell, the felspars are extremely fresh, almost glassy, with a few calcite stringers; the augites are completely changed to chlorite and calcite and the olivine has altered to a similar dark red mineral. There are numerous other examples of the same type of olivine alteration. The optical properties given show that this red decomposition mineral is probably the iddingsite of Ross & Shannon.

If we assume that increasing cloudiness of the felspars is indicative of increasing general alteration it becomes clear that the iddingsite is not a stable alteration product but that it too changes as alteration progresses. With increase in the veining of the felspar by calcite, iddingsite, as seen with the microscope, becomes lighter in colour, particularly towards the centre of the crystal, the dark red changes to orange, and the orange to yellow. Some crystals, like those in one of the basalts of Arkleton Hill, are brilliantly variegated, with red and orange in alternating bands. This process continues until the stage is reached where the 'iddingsite' pseudomorphs consist of a dark red border, frequently almost opaque and red in reflected light, and an interior portion of a distinct yellow colour. Many of the basalts below Langholm Bridge show this type of olivine alteration. Frequently the yellow has a greenish tinge. The optical properties of the yellow mineral agree closely with those of bowlingite in all respects, except the birefringence, which is low at .010. With increasing alteration the bowlingite becomes very pale green and finally breaks down into a cryptocrystalline aggregate of chlorite flakes (R.I. 1.56).

The majority of the pseudomorphs composed of the bowlingite have a thick dark border, but there are some which have only the narrowest opaque fringe. The change from iddingsite to bowlingite is not a normal replacement, but rather a gradual transition with intermediate stages. The process has a possible connection with carbonatisation, for in the rocks where calcite is scarce, dark red iddingsite is found and in those where calcite is plentiful the yellow bowlingite occurs.

Some pseudomorphs after olivine have either rims or cores of calcite.

These occur especially where calcite is plentiful as in the rocks of Ettleton Sike. The process cannot be traced, however, and the relation of this type of pseudomorph to the other types is not known.

In the weathered skin of the olivine basalts the olivine pseudomorphs are all very dark red and heavily charged with iron ores so that their internal arrangement is obscured.

The distribution of iddingsite is significant, for it bears no relation to the surface of the flow, but is uniformly distributed throughout. It occurs in rocks which are very little weathered, in which the felspars are quite fresh and in which the augites are only slightly changed. Also it does not occur in all basalts in the district—many olivine-bearing rocks yield 'serpentine', not iddingsite. Lastly it is earlier than the chlorite, which has been assigned to a late magmatic stage in development. The above facts confirm that iddingsite is a true deuteric mineral and not the product of normal weathering.

(c) Carbonatisation

All the basalts, except the very freshest, contain calcite, in some cases to such a degree that they effervesce strongly with dilute hydrochloric acid. The calcite occurs in many forms. It replaces fresh glassy felspar by veinlets and stringers, as in the Dunsapie basalt of Foots Burn; it occurs with iddingsite as a pseudomorph after olivine; it replaces in part the augite phenocrysts, as in the basalts of the upper Tarras Water, and it is scattered widespread throughout the groundmass of all the lavas.

In the basalts of Raegill Burn, the calcite crystals are small and scattered; they are quite shapeless with extremely irregular margins. In the basalts of Ettleton Sike, which are very thoroughly impregnated, calcite occurs in a bewildering variety of forms, from stringers to irregular patches composed of an accumulation of smaller crystals; whilst in some of the Skipper's Bridge rocks calcite occurs in big plates with extremely crenulate margins. The feature of all these occurrences is the irregular form of the calcite patches and their extremely uniform dissemination (cf. Pallister, 1952, 344).

There is no evidence to suggest the source of the calcite, but in view of its uniform dissemination throughout a flow, its close association with chlorite, which it may rarely precede in vesicles, and the very limited reaction between lava and observed limestone xenoliths, it is confirmed that much of the calcium was in the lava prior to its eruption and that calcite is a late magmatic product.

Considering the principal minerals, it will be seen that there is reasonable evidence to indicate that the major complex changes which they have undergone are a response, not to atmospheric conditions, but to the influence of fluids, which most probably came from the magma itself and which were present at a comparatively early stage in the cooling history.

7. CHEMICAL ANALYSES

Most of the igneous rocks are altered and comparatively few have been analysed chemically. Of the four published here, Table I, two are of fresh

TABLE I

	1	2	3	4	5	6
SiO_2	48.9	47.6	45.6	50.1	49.14	48.28
TiO_2	1.9	1.9	2.5	1.4	2.72	2.34
Al_2O_3	16.0	18.3	18.2	15.2	15.32	16.32
Fe_2O_3	3.4	4.4	4.7	1.1	9.82	3.26
FeO	8.1	5.2	6.2	8.8	1.31	6.52
MnO	0.2	0.2	0.2	0.2	0.24	0.23
MgO	6.6	2.5	2.8	7.7	5.34	7.43
CaO	8.0	7.8	7.8	7.7	4.46	5.72
Na_2O	2.4	3.9	3.6	3.5	3.23	3.38
K_2O	1.1	1.8	2.0	1.8	1.55	1.02
H_2O+	2.1	2.7	2.4	1.5	3.26	3.02
H_2O-	0.8	0.5	0.5	0.3	1.24	1.88
P_2O_5	0.4	1.0	0.7	0.6	0.72	0.47
CO_2	traces	2.4	2.7	NIL	1.35	traces
	99.9	100.2	99.9	99.9	99.70	99.87
qz	2.1	5.6	3.7	—	—	—
or	6.7	10.6	11.7	10.6	—	—
ab	20.4	33.0	30.4	29.4	—	—
an	29.5	17.2	17.5	20.8	—	—
co	—	3.6	3.7	—	—	—
di	6.4	—	—	11.3	—	—
hy	22.4	9.1	10.8	3.1	—	—
ol	—	—	—	17.5	—	—
il	3.7	3.6	4.7	2.7	—	—
mt	4.9	6.5	6.7	1.6	—	—
ap	1.0	2.4	1.7	1.4	—	—
cc	—	5.6	6.1	—	—	—

1. Extrusive (?) hypersthene bearing Dunsapie Basalt, Greybanno Sike, Cooms Fell. Analyst: W. H. Herdsman (new analysis).
2. Intrusive basalt, intermediate in type between Jedburgh Basalt and Mugearite, slightly altered, Raegill Burn (new analysis).
3. Intrusive Jedburgh Basalt, slightly altered, Greena Hill, Liddisdale. Analyst: W. H. Herdsman (new analysis).
4. Intrusive Dalmeny Basalt, Tinnis Hill summit. Analyst: W. H. Herdsman (new analysis).
5. Lava, Jedburgh-type Basalt, Bluff east of Haregills. Analyst: W. H. Herdsman. Pallister, 1952.
6. Lava, Dalmeny-type Basalt, Kirtle Water, 1200 feet north of Setthorns. Analyst: W. H. Herdsman. Pallister, 1952.

olivine-bearing rocks which can be compared with those of other basalts; the other two contain over 2% of CO_2 and may not be compared directly with the analyses of fresh rocks.

(a) Analysis 1

The Dunsapie basalt of Cooms Fell calls for little comment; it has rather high SiO_2 but otherwise resembles normal Dunsapie rocks. On the AFM diagram (Fig. 3) it lies exceedingly close to the average of the Dunsapie and Dalmeny types of Tomkeieff (1937).

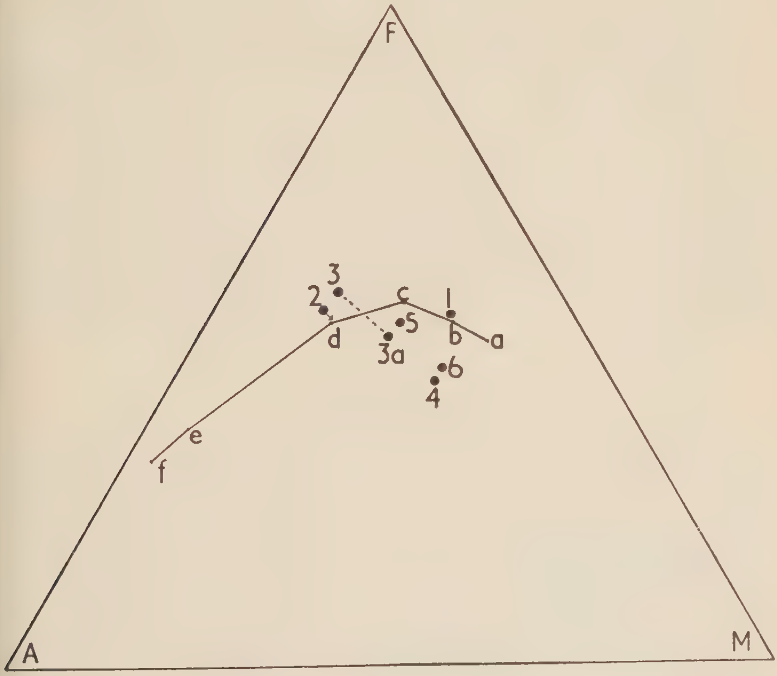


Fig. 3. Plot of the compositions of the Carboniferous igneous rocks in terms of FeO + Fe_2O_3(F), MgO(M) and alkalis (A)

a = average olivine basalt of Craiglockhart–Hillhouse type
b = average olivine basalt of Dunsapie–Dalmeny type
c = average olivine basalt of Markle–Jedburgh type
d = average Mugearite
e = average Trachyte
f = average Phonolite

Analyses a–f are from Tomkeieff (1937)
Analyses 1–6 are as for Table I

(b) Analyses 2 and 3

The transition Mugearite–Jedburgh basalt of Raegill Burn and the Jedburgh basalt of Greena Hill are remarkably alike chemically, differing mainly in the amounts of their SiO_2, FeO and Na_2O. On the AFM diagram (Fig. 3) the transition rock (anal. 2) lies close to the average Mugearite (Tomkeieff, 1937); petrographically also it resembles the Mugearites. There are significant differences, however, especially in the alkalis, silica and lime.

The Jedburgh basalt (anal. 3) is abnormally low in MgO and in consequence lies well above the curve of average compositions of the Scottish Carboniferous extrusives. This may be due to alteration, because it is a feature of a great many of the altered rocks that carbonatisation and a loss in MgO go hand in hand. If we make the extreme assumption that all the carbonate replaces magnesian olivine exclusively and that no MgO is lost other than by replacement, then we can work back to a maximum figure for MgO in the rock. The 2.7% of CO_2 of anal. 3 replaces about 2.6% of MgO so that before replacement of olivine by calcite the MgO would have been $2.6 + 2.8$, i.e. 5.4. We can recalculate the analysis for the AFM diagram (Fig. 3), using this amended figure. We get point 3a. It is, of course, unlikely that the carbonate replaced only a magnesian olivine. Any other replacement will give an original MgO figure of less than 5.4. It seems likely therefore that a reasonable position for the original Greena Hill rock is between points 3 and 3a, that is, nearer the average line.

(c) Analysis 4

The Greena Hill rock was correlated with the Tinnis Hill rock (anal. 4) by Lady M'Robert; the AFM diagram brings out the difference between the two rocks. It is most unlikely that the two rocks are two expressions of the same magma.

The Tinnis Hill rock lies well away from the line of average compositions, and the low Fe/Mg ratio coupled with high alkalis is anomalous. It is difficult to explain why this is so; unfortunately the fine nature of the rock precludes a mineralogical explanation. The rock is not unique by any means. It can be matched by another Dalmeny basalt in the Kirtle Water, north of Setthorns, eleven miles to the south-west (Pallister, 1952).

Modes are not quoted. Modal analyses were, in fact, made of all the rocks sectioned, but an assessment of their value in the light of errors introduced by the combination of fineness of grain-size and the overlap of grains led to the conclusion that they were largely valueless. To illustrate, the modal percentage of calcite in the Raegill Burn rock was measured as 17.6; the maximum quantity possible from the chemical analysis is 5.6. The discrepancy is enormous and is, without doubt, due to the small size of the calcite grains coupled with their high R.I. In the face of possible errors of this sort and magnitude, modal analyses are not given.

8. CONCLUSIONS

Vulcanicity took place near Langholm three times during the Carboniferous period. Firstly at the beginning of the period, secondly during the deposition of the Cementstones and thirdly immediately after the deposition of the Fell Sandstones.

The earliest lavas formed a continuous plateau whilst the later ones gave rise to separated patches of igneous rocks. All the lavas are of olivine basalt of which Dalmeny, Jedburgh and Dunsapie basalts are of widest occurrence. All were extensively affected by late magmatic fluids which altered the olivines, augite and felspars in that sequence. The alteration was progressive and was largely completed before the lavas finally ceased flowing.

ACKNOWLEDGMENTS

The author wishes to acknowledge his indebtedness to the University of Nottingham for its generosity in making a grant to defray field expenses, and to the Assistant Director of the Geological Survey (Scottish Office) for his kindness in allowing him to see the unpublished field maps of the early surveyors in the Canonbie Coalfield.

EXPLANATION OF PLATE 1

A. Dunsapie Basalt, Cooms Fell

This illustrates the stellate clusters of large hypersthenes rimmed by monoclinic pyroxene. Partially altered olivines occur, top centre, and left centre, and a cross-section of augite is in the centre of the figure.

B. Jedburgh Basalt, Whita Hill

A large vesicle is cracked and flattened; its chlorite lining has broken into small pieces which are now separated and enclosed in calcite. A small tongue of lava, lower left, is now inside the vesicle and is highly carbonated. This is taken to indicate that chloritisation occurred before the cessation of movement of the lava-flow.

C. Dalmeny Basalt, Langholm Bridge

The dark patches in the centre represent altered olivines. On the right is a chlorite 'lake' with its fibrous margins and an enclosed felspar, whilst on the left is another chlorite 'lake' into which partially replaced felspars project.

REFERENCES

Barrett, B. H. & J. E. Richey. 1945. Economic Geology of the Canonbie Coalfield. *Wartime Pamph. geol. Surv. Eng., No. 42.*

Flett, Sir J. S. 1908. On the Mugearites. *Summ. Progr. geol. Surv., Lond.*, 119–26.

Geikie, Sir A. 1897. *The Ancient Volcanoes of Britain*, **1**, London.

Hess, H. H. 1941. Pyroxenes of Common Mafic Magmas. *Amer. Min.*, **26**, 515,517.

———. 1949. Chemical Composition and Optical Properties of Common Clinopyroxenes. *Amer. Min.*, **34**, 621–66.

MacGregor, A. G. 1928. Classification of Scottish Carboniferous Basalts and Mugearites. *Trans. geol. Soc. Glasg.*, **18**, 324–60.

M'Robert, Lady R. W. 1916. Igneous Rocks of Teviot and Liddisdale. *Trans. Edinb. geol. Soc.*, **11**, 86.

Pallister, J. W. 1952. The Birrenswark Lavas, Dumfriesshire. *Trans. Edinb. geol. Soc.*, **14** (3), 336–48.

Ross, C. S. & E. V. Shannon. 1925. The Origin, Occurrence, Composition and Physical Properties of the Mineral Iddingsite. *Proc. U.S. nat. Mus.*, **67** (7).

Tomkeieff, S. I. 1937. Petro-chemistry of the Scottish Carboniferous–Permian Igneous Rocks. *Bull. volcan., Série 2*, **1**, 61–87.

A New Mesozoic Terebratellid Brachiopod

by GRAHAM F. ELLIOTT

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ABSTRACT: A new terebratellacean brachiopod, *Australiarcula artesiana* gen. et sp. nov., is described from Lower Albian strata in South Australia. It is the earliest member yet found of the predominantly southern-hemisphere Tertiary family Terebratellidae, antedating such European Cretaceous genera as the Senonian *Magas*.

1. INTRODUCTION

AMONGST the long-looped brachiopods, the family terebratellidae is a distinctively southern-hemisphere group, its members living in present-day waters off Antarctica, Australia, New Zealand and southern South America, and locally occurring fossil in the Australasian Tertiary with an abundance reminiscent of the terebratulidae in the English Jurassic. In the northern hemisphere there are a few representatives, such as *Tanakura* (Tertiary) and *Diestothyris* (Recent) in the Asiatic North Pacific area, but in Europe only the tiny rarities *Mannia* (Pliocene) and *Lutetiarcula* (Eocene) have been tentatively referred to the family: the former is a rhynchonellid and the latter is represented by one incomplete specimen only.

In the Cretaceous, however, terebratellidae occur noticeably in Europe. Of these, *Magas* and *Trigonosemus* are found in the Senonian from England to Russia and to Turkey respectively, and *Rhynchora* and *Rhynchorina* at the same horizon in northern Europe, while at a lower level the Cenomanian *Dereta pectita* (J. Sowerby) and related species may be referable to the family. In Australia and South America species of *Bouchardiella* are Senonian. Because of this rather inconclusive distribution a European origin has been considered possible for the family, with Tethyan migration to the southern hemisphere (Allan, 1940; Elliott, 1951, 1952).

In reading the recent account of the geology of South Australia edited by Glaessner & Parkin (1958) the writer noted the record of Lower Albian

Terebratella beds in the Great Artesian Basin area. Professor M. F. Glaessner of Adelaide University readily and generously lent specimens of these brachiopods on request. They prove to be of a new, undoubtedly terebratellid genus, intermediate in morphological characters between members of the subfamilies Bouchardiinae and Magasinae. It is the earliest terebratellid genus known, and suggests that the family originated in the southern hemisphere, and that the European Cretaceous genera were Tethyan migrants which, once extinct, were not renewed. The later, East Pacific Tertiary migrants to the North Pacific have survived to the present day.

2. SYSTEMATIC DESCRIPTION

Superfamily: *TEREBRATELLACEA* Allan, 1940

Family: TEREBRATELLIDAE King, 1850

Subfamily: MAGASINAE Davidson, 1886

Genus: **AUSTRALIARCULA** gen. nov.

Terebratellidae with the external morphology and delimited symphytium of the Magasinae, and with a primitive magadiniform loop, but also with the massive cardinalia and internal shell-thickening of the early Bouchardiinae. Type species: *A. artesiana* sp. nov. Cretaceous, Lower Albian: Great Artesian Basin, South Australia.

Australiarcula artesiana sp. nov.

Plate 2. Figs. 1–7; text Figs. 1–3

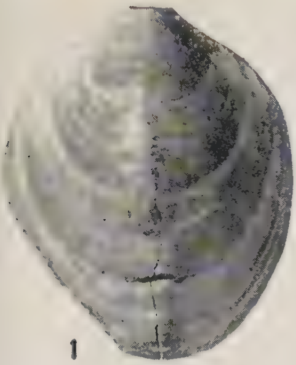
Diagnosis. Shell about 15 mm. long, 10 mm. wide and 7 mm. deep, ovoid narrowing anteriorly with median dorsal sulcus matched by ventral keel: test smooth, commissure sulcate. Beak erect, foramen permesothyrid, symphytium concave, beak-ridges sharp, hinge-line gently sloping. Hinge-teeth stout with grooved swollen bases. Sockets deep, socket-ridges strong, cardinal platform solid with posterior muscle-pit, septum high anteriorly, loop primitive magadiniform.

Holotype. The specimen figured in Plate 2, Figs. 1, 2, 4, 6, from the Lower Albian (Cretaceous) *Terebratella* beds, Lower Tambo Formation, Rolling Downs Group: Santos No. 1 bore, 429½ feet, near Oodnadatta, South Australia. Reg. No. Geol. Dept. University of Adelaide, F.15278.

Paratypes. The specimens figured in Plate 2, Figs. 3, 5, 7, same locality and horizon. Reg. Nos. F.15279, 80, 81.

Description

(*a*) *External.* This shell is smooth, the valves being marked only by lines of interruption of growth, and is finely and regularly punctate: it is ovate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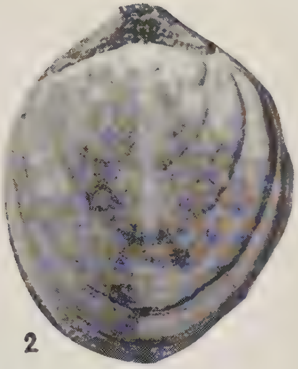
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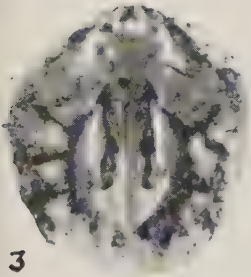
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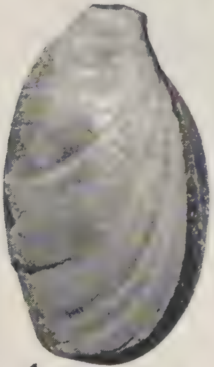
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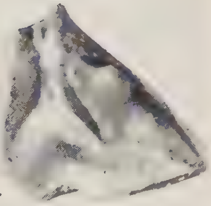
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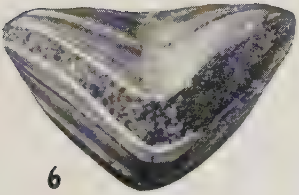
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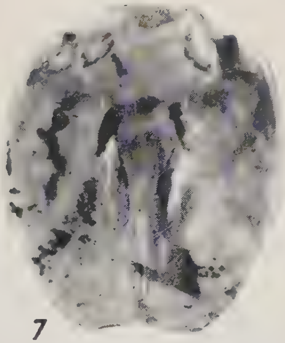
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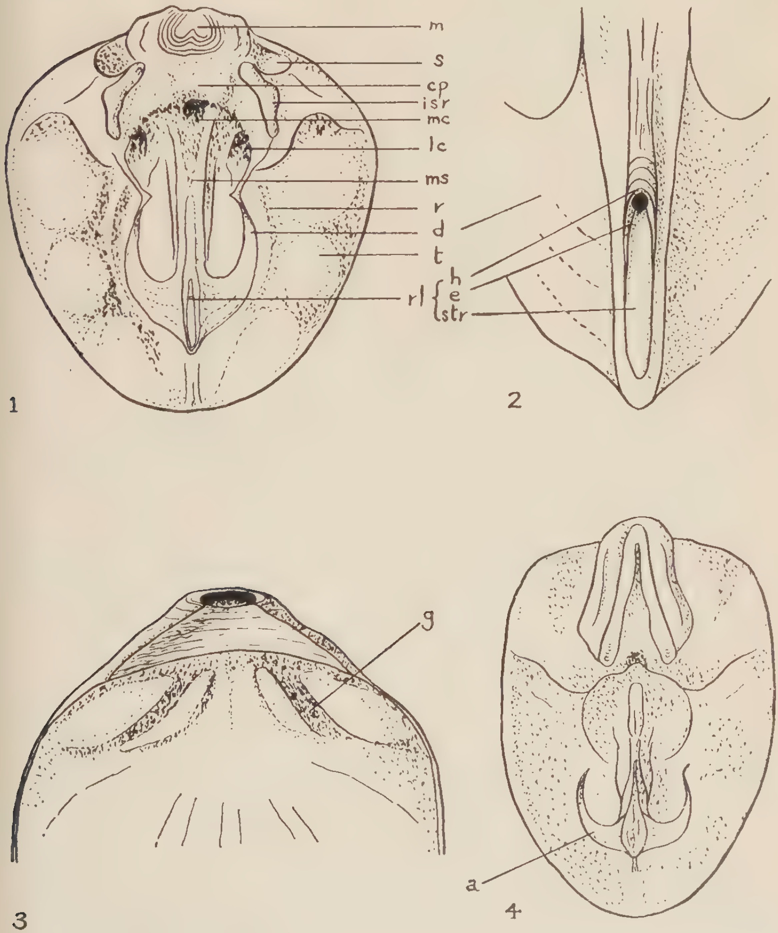
in outline with an anterior tapering, the greatest width being a little posterior of mid-length. The dorsal valve is flattened near the umbo: anterior of this it is concave with a wide rounded median sulcus. The ventral valve is convex with lateral slopes from a median rounded keel, and the resulting anterior commissure is sharply sulcate. The beak is moderately produced and erect, with permesothyrid foramen; fairly sharp beak-ridges and a gently sloping hinge-line enclose a wide low concave symphytium, delimited from the beak-ridges by grooves.



Australiarcula and *Bouchardia*

(*b*) *Ventral valve interior.* The posterior part of the valve is thickened, and the interior of the beak much constricted: anteriorly the valve is much thinner. The hinge-teeth are stout with swollen bases, in which are deep grooves corresponding to the dorsal socket-ridges.

(*c*) *Dorsal valve interior.* This valve is much thickened, especially posteriorly, where the cardinalia are fused into a massive cardinal platform. The sockets are posterior in position and deep, with low outer-socket ridges and an area of thickened test anteriorly. They are overhung by prominent inner socket-ridges which are the lateral walls of the central cardinal platform. The upper (ventral) surface shows as a massive rounded swollen boss anteriorly: posteriorly there is a smaller central heart-shaped muscle-pit, with the indentation anterior, showing concentric lines of growth, and with the rounded outer edges rising above the level of the posterior platform. This structure slopes to the posterior edge of the valve. The septum is low and broad posteriorly, showing a median groove, and buttresses the cardinal platform in an embayment: to left and right of the septum are caves or hollows in the anterior wall of the platform, with a third smaller cave above the median septal groove. Anteriorly the septum thins and rises steeply, leaning forward like the prow of a ship with a low ridge continuing its course on the valve floor: the posterior septal groove changes anteriorly to a rounded septal crest. Left and right of the median septum thick sharp-crested outwardly curved ridges on the valve-floor follow the course of the descending branches of the loop above and delimit deep trenches to left and right of the septum: these ridges are convex in section outwardly and slightly concave and steep within. Outside them the valve-floor is irregularly thickened in rounded areas leaving grooves between, giving it a puckered appearance.

The descending branches commence high in the anterior wall of the cardinal platform, without crural bases, as very delicate threads curving inwards for a short distance to tiny crural points: they then curve anteriorly outwards and slightly downwards (dorsally) to twist round, and rising and widening very rapidly attach themselves left and right as broad triangular wings to the high anterior septum. There are no ascending branches as strictly defined, but above the broad attachments of the descending branches the steep smooth crest of the septum shows a minute flattened strip with very thin raised edges which unite posteriorly to form a tiny roofed-in groove or oblique perforation.

3. CONCLUSIONS

The significance of this Australian Albian occurrence of an undoubted terebratellid, the earliest so far known, for the history of these brachiopods, has already been mentioned. Intrinsically, *Australiarcula* shows characters later characteristic of different subfamilies. The massive cardinalian platform with anterior caves is a feature of the Bouchardiinae, and compares especially with *Bouchardiella* if the posterior muscle-pit is taken into consideration. *Bouchardiella* is the Upper Cretaceous forerunner of *Bouchardia* and *Neobouchardia* in the Tertiary, and is represented in the Western Australian Senonian by *Bouchardiella cretacea* (Etheridge). The external form of the shell, symphytium and beak characters of *Australiarcula*, however, are like those of the Tertiary Magasinae, particularly *Magadina*. *Australiarcula* agrees with this genus in the symphytium delimited by grooves, whereas in *Bouchardia* and its allies this structure is fused with the ventral valve. The curved ridges on the dorsal valve-floor are also common to the two genera compared.

The loop of *Australiarcula* is not that of *Bouchardia* (text Fig. 4) and its allies, in which there are no descending branches but only rudimentary lamellae, interpreted as an incomplete 'ascending structure', on the septum. In *Magas pumilus* J. Sowerby of the Cretaceous and *Magadina browni* Thomson of the Tertiary, the loop shows descending branches as well as the incomplete septal structure, and in the Recent *Magadina cumingi* (Davidson) the septal structure is completed as a ring. Now *Australiarcula* shows the descending branches, but the septal structure, the tiny groove and perforation described above, is rudimentary. Nothing is known like it in the Terebratellidae, where early septal rings are the rule and early hoods are rare (a ring-like hood is described by Thomson (1915b) for an early stage of *Terebratella inconspicua* G. B. Sowerby), and even if it is compared with very early growth-stage loop-structures in the Dallinidae, such as Beecher (1895) described for *Dallinella obsoleta* (Dall), it is still anomalous in view of its occurrence in *Australiarcula* in an adult shell. It is therefore described here as a primitive magadiniform loop (cf. Thomson, 1927; Elliott, 1953). It seems best to accept the fact that this is yet another combination of characters in a new genus, a familiar brachiopod phenomenon, and in view of the known geological age to recall the statement of Thomson (1915a, 402) '. . . it is probable that *Bouchardia* is a retrograde genus from a forerunner of *Magadina*. . . .' *Australiarcula* is the best claimant yet to be this hypothetical ancestor.

EXPLANATION OF PLATE 2

All figures of *Australiarcula artesiana* gen. et sp. nov. × 3.3 approx., from the Cretaceous (Lower Albian) *Terebratella* beds, Lower Tambo Formation, Rolling Downs Group, Santos No. 1 bore, 429½ feet, near Oodnadatta, South Australia. Reg. Nos. Geol. Dept. Univ. Adelaide, South Australia.

1. Holotype, dorsal view. No. F.15278.
2. Holotype, ventral view.
3. Paratype, brachial interior, showing cardinalia with posterior muscle-pit and prominent socket-ridges, median septum and broken loop, and curved ridges on the valve-floor. Tiny crystals of dark pyrites line the valleys between areas of shell-thickening on the valve-floor. No. F.15279.

4. Holotype, lateral view.
5. Paratype: broken portion of the posterior interior of a ventral valve. The midline of the valve is to the viewer's left: to the right the massive base of the hinge-tooth is cleft by a deep groove for the reception of the opposing socket-ridge. No. F.15280.
6. Holotype, anterior view.
7. Paratype, brachial interior to show the curious groove and roofed-in pore on the anterior median septum: traces of the attachments of broken descending branches to left and right. No. F.15281.

EXPLANATION OF TEXT FIGURES

1. *Australiarcula artesiana*, dorsal valve interior, drawing based on specimen figured Plate 2, Fig. 3, with branches of loop restored.

2. Anterior portion of the septum and descending branches much enlarged, to show the rudimentary loop-structure on the septum. Based on the originals of Plate 2, Figs. 3, 7, together with a third specimen.

3. Restoration of ventral valve interior, to show deep grooves in the swollen bases of the hinge-teeth. Plate 2, Fig. 5, is a portion of a broken valve showing one of these structures.

4. *Bouchardia rosea* (Mawe), a recent brachiopod from off the Brazilian coast. Dorsal valve interior, × 4, for comparison with that of *Australiarcula*. Following Davidson and later workers, the horns of the loop (a) are homologised not with the descending branches (d), which they resemble, in *Australiarcula*, but with the structure (rl) on the septum.

a = modified ascending branch of loop, cp = cardinal platform, d = descending branch of loop, e = raised edge of str., g = deep groove in base of hinge-tooth, h = rudimentary hood, isr = inner socket-ridge, lc = lateral cave, m = muscle-pit, mc = median cave, ms = median septum, r = ridge on valve-floor, rl = rudimentary loop-structure, s = socket, sc = septal crest, str = flattened strip, t = thickening of valve-floor.

REFERENCES

Allan, R. S. 1940. A Revision of the Classification of the Terebratelloid Brachiopoda. *Rec. Canterbury* [*N.Z.*] *Mus.*, **4**, 267–75.

Beecher, C. E. 1895. The Development of *Terebratalia obsoleta* Dall. *Trans. Conn. Acad. Arts Sci.*, **9**, 392–5.

Elliott, G. F. 1951. On the Geographical Distribution of Terebratelloid Brachiopods. *Ann. Mag. nat. Hist.* (12), **4**, 305–34.

———. 1952. The Internal Structure of some Western Australian Cretaceous Brachiopods. *J. roy. Soc. W. Aust.*, **36**, 1–21.

———. 1953. Brachial Development and Evolution in Terebratelloid Brachiopods. *Biol. Rev.*, **28**, 261–79.

Glaessner, M. F. & L. W. Parkin. 1958. The Geology of South Australia. *Journ. Geol. Soc. Australia*, **5** (2), 96. (Chap. 7, R. C. Sprigg and staff, 'The Great Artesian Basin in South Australia', 88–101.)

Thomson, J. A. 1915a. Brachiopod Genera: the position of Shells and Magaselliform Loops, and of Shells with Bouchardiform Beak Characters. *Trans. N.Z. Inst.*, **47**, 392–403.

———. 1915b. Additions to the knowledge of the Recent Brachiopoda of New Zealand. *Ibid.*, **47**, 404–9.

Some Comments on the Raised Beach Platform of South-West Caernarvonshire and on an Unrecorded Raised Beach at Porth Neigwl, North Wales

by J. B. WHITTOW

Received 13 May 1958

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ABSTRACT: The discovery of a raised beach deposit in the Lleyn peninsula has prompted the author to re-examine the raised platform of marine abrasion which has been recorded at a few localities in south-west Caernarvonshire. The latter platform was found to be entirely devoid of beach deposits and is undoubtedly of pre-glacial or interglacial age, whereas the raised beach deposit of Porth Neigwl appears to have been formed in post-glacial times.

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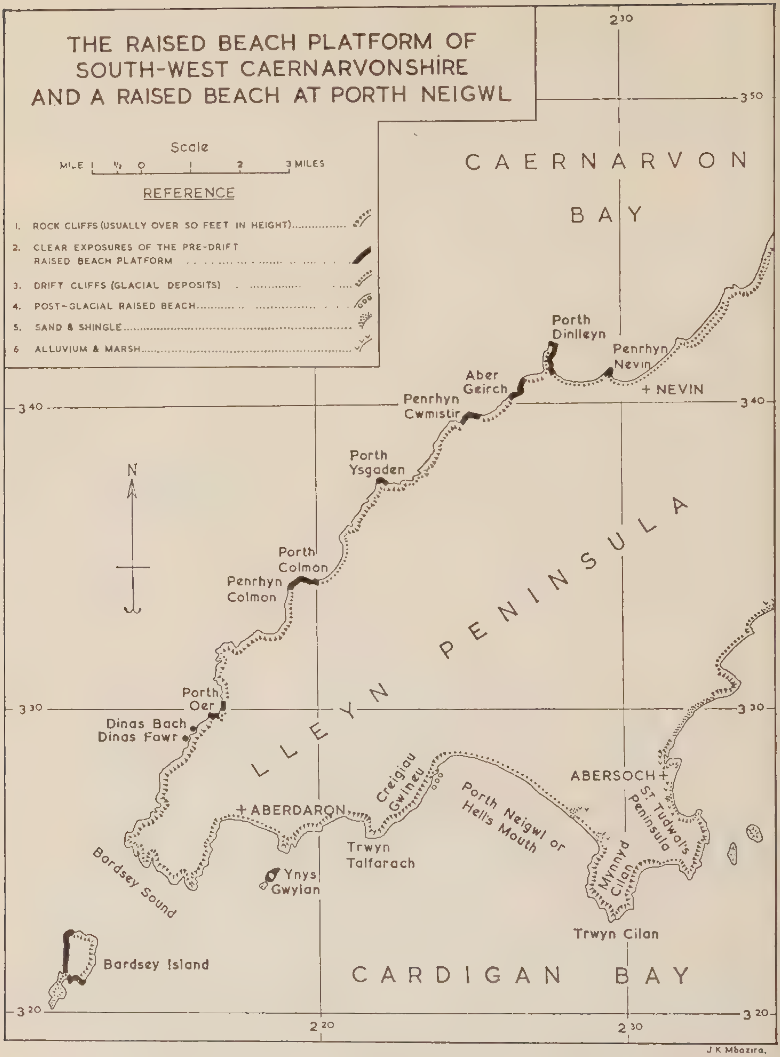
1. THE PRE-DRIFT RAISED BEACH PLATFORM

ON THE western coast of the Lleyn peninsula between Bardsey Island and Nevin a marine abrasion platform occurs at an average elevation of ten feet above H.W.M. and in every locality it is overlain by glacial drift. It was first mentioned by Jehu (1909), and later by Matley and others (1939), but it appears that none of the authors examined it at all the sites where it is uncovered from beneath the drift. The present writer has mapped all the localities where the platform is clearly exposed (Fig. 1), but only in one place are traces of the old cliff distinguishable. Near the lifeboat station of Porth Dinlleyn the drift has been removed (possibly by human agencies) sufficiently to uncover a wave-cut notch which can be traced for a few yards at a height of approximately twenty-five feet O.D. It is possible that at this site the rock exposure on which the notch is displayed may be an old sea-stack partially buried by the drift. Indeed it is interesting to speculate whether the curiously shaped peninsula of Porth Dinlleyn is in reality a series of sea-stacks rising above the raised beach platform, and now tied to the mainland by a thick cover of drift.

The relationship between the Pre-Drift Raised Beach Platform and the modern wave-cut rock bench is not always a simple one. In the majority of cases the higher platform has been notched at its seaward end by wave attack of the present sea-level, but there are a few sites where this modern notching is not clearly marked and where the seaward end of the raised



J K Mbazira.

Fig. 1

rock platform is rugged and broken. It is noteworthy that on the opposite shore of the Irish Sea the raised beach platform of the Wicklow–Wexford coast sometimes exhibits a similar characteristic (Martin, 1955). A feature of the utmost importance is that the raised platform stands at an elevation beyond the reach of all but the most exceptional storm waves, and as

A

B

To face p. 33]

a result it is often overgrown with lichens, mosses and grass. In some localities a few small sea-stacks are relict on the platform and they may be indicative of the fact that the still-stand at approximately twenty-five feet O.D. probably existed for only a relatively short period, the sea having withdrawn while the coastline was still in the youthful stage of the marine erosion cycle. Nevertheless, it has been pointed out that whilst sea-stacks '. . . reach their most abundant development before maturity is attained, they may also be present on fully mature shores' (Johnson, 1919). A definite decision on this point, however, cannot be made, since the presence of the drift makes it impossible to distinguish the width of the platform or to determine the plan of the raised beach coastline. The most that can be said from the available evidence is, firstly, that the failure to discover more than one exposed example of a wave-cut notch behind the platform may mean that the width of the platform beneath the drift is considerable, therefore implying a lengthy period of marine abrasion; secondly, that the platform has been so perfectly planed across steeply dipping and contorted rocks at some sites that one is persuaded to think in terms of a prolonged marine cycle. Since the platform has been severely grooved by ice-action at a number of localities it is also possible that ice may have played no small part in the smoothing of the platform surface. But the fact that the small sea-stacks, which rise from the platform at other places, have not been swept away suggests that glacial action was very localised and could not have been of such great significance in the general bevelling of the platform.

The southernmost example of the raised rock platform in Lleyn occurs on Bardsey Island, where the low level bench west of Mynydd Enlli seems to be a composite feature, i.e. drift overlying the raised beach platform. The latter is well exposed near the landing-place, but circumstances prevented the author from making a full investigation of the remainder of the island.

The platform is also exhibited on one of the Ynys Gwylan (Gull Islands) in Aberdaron Bay. It is covered by a remnant of drift on Ynys Gwylan Fawr but a remarkable stack rises to 100 feet in height above the rock platform, together forming a conspicuous feature when seen in profile from Aberdaron village.

From Bardsey Sound to Porth Oer the sea cliffs are precipitous and the platform is not represented except possibly at two drift-capped islets, Dinas Fawr and Dinas Bach. Farther north, however, an excellent example occurs at Porth Oer, at either end of the so-called 'Whistling Sands'. The average height of the rock platform, which here cuts across highly contorted Pre-Cambrian rocks, is some twenty feet O.D., but nowhere is the wave-cut notch exposed from beneath the drift. An interesting feature at Porth Oer is the way in which the platform is seen to truncate the top of the modern sea-stacks a short distance off-shore (Plate 3A).

Continuing northwards the platform can be traced for some distance near to Penrhyn Colmon, and at Porth Colmon can be found the finest example in the Lleyn peninsula. It is at this locality that small sea-stacks are exhibited. The platform appears to be present in a fragmented state at Porth Ysgaden and also at Penrhyn Cwmistir, although better and more accessible exposures are to be found at Aber Geirch. At this point the platform is somewhat higher than elsewhere on the coast of Lleyn, but it must be borne in mind that this is a headland site (despite its name), and that the Afon Geirch is at present probably following a channel excavated as a result of glacial diversion (Whittow, 1957). The slightly higher elevation of the platform at a headland locality agrees with the findings on the east coast of Ireland (Stephens, 1957). On the small peninsula of Porth Dinlleyn several houses have utilised the narrow site offered by the rock platform, being perched precariously on the brink of the modern high-water mark and overshadowed by precipitous cliffs of drift. The platform, which near the lifeboat station is finely glaciated, disappears beneath these drift cliffs as it is traced towards the centre of the bay, only to reappear on the headland of Penrhyn Nevin. This is the northern limit of the platform in the Lleyn peninsula so far as is known.

Failure to distinguish the platform elsewhere in the Lleyn peninsula must be attributed to two reasons. In the first place the present cycle of marine erosion may have been responsible for its destruction on some stretches of the coastline. Secondly, in some areas it may be present beneath the extensive drift cover, particularly along the south coast of Caernarvonshire. Nevertheless, at no point has the author been able to identify the platform with certainty between the Ynys Gwylan and Portmadoc. It might be expected that such headlands as Careg-y-Defaid and Careg-yr-Imbill (near Pwllheli) would display notching at the appropriate elevation but unfortunately both have been extensively refashioned by quarrying. Farther east the headlands of Pen-y-Chain and Criccieth Castell are also without convincing evidence although it has been suggested that a rock bench two feet above high-water mark and overlain by 'head' at Criccieth may be the equivalent of the 'pre-glacial raised beach platform' (Fearnsides, 1910). The author has examined this site and also the headlands of Rhiw-for-Fawr and Craig-Ddu to the east of Criccieth but is not convinced that the rock platform under discussion is present.

Although it has been suggested by Jehu that certain superficial deposits in Porth Oer may represent actual raised beach deposits, the author has found no evidence to support this possibility. At two localities (Porth Oer, Penrhyn Nevin), a thin layer of angular rock rubble or 'head' lies on the platform and in each case is overlain by a drift of uncertain age. Elsewhere the so-called 'Upper and Lower Boulder Clays' (Jehu, 1909) alternately rest immediately on the platform, and nowhere has the author discovered any calcreted or concreted beach material associated with the latter. This is hardly surprising, perhaps, for the glacial striations indicate that the platform must have been severely scoured by Irish Sea ice moving on-shore from a northerly direction.

In elevation and form this platform of Lleyn is similar in every respect to the so-called *Patella* beach rock platform which has been widely recognised in the southern half of the British Isles. Since it has not been recorded elsewhere in North Wales the nearest localities for comparative purposes are to be found in eastern Ireland and in Gower, South Wales. On the south-east coast of Ireland a rock platform at a similar elevation to the one in southern Caernarvonshire is overlain by beach deposits which themselves pre-date two glacial drifts. The lower of these drifts (Eastern General) has been referred to the Riss glaciation by Mitchell (1951), so that the Irish rock platform is at least as old as the Mindel–Riss Interglacial. The *Patella* beach platform of Gower has been tentatively placed in the Mindel–Riss Interglacial by reason of its overlying deposits (Arkell, 1943) but doubts are now being expressed for this dating. It is noteworthy that raised beach investigation in Ireland is emphasising the danger of assuming that beach deposits are everywhere contemporaneous with the rock platform on which they rest (Stephens, 1957; Stephens & Synge, 1958).

In conclusion it may be said that the Pre-Drift Raised Beach Platform in the Lleyn peninsula cannot be precisely dated. It lacks beach material which even if present would not necessarily be of the same age as the platform, whilst, in addition, the age of the overlying glacial deposits has not been accurately determined in all localities. In the author's opinion the 'Lower Boulder Clay' in the Lleyn peninsula appears to have been deposited by the initial advance into the peninsula of an Irish Sea ice-sheet, and it may be possible, therefore, to regard it as the oldest of the 'New Drifts' (Whittow, 1957). If tentative correlations must be made then the 'Lower Boulder Clay' of Lleyn may be equivalent in age to the Cornovian glaciation (Arkell, 1943) and the Midland General glaciation of Ireland which Charlesworth equates with the South Wales end-moraine (Charlesworth, 1929). Although deposits of head underly the 'Lower Boulder Clay' in a few localities in Lleyn it cannot necessarily be assumed that the head represents an 'Old Drift' deposit or is equivalent to part of Arkell's Catuvellaunian glaciation or the Eastern General glaciation of Ireland. The most that can be said from the available evidence is that the platform in the Lleyn peninsula is probably older than the British equivalent of the Würm glaciation. By comparison with similar rock platforms at approximately the same elevation on other coasts of the Irish Sea it appears that the platform may even be as old as the Mindel–Riss Interglacial, and there is no reason to suppose that it is not much older.

2. THE POST-GLACIAL RAISED BEACH

The bay head of Porth Neigwl (Hell's Mouth) is composed almost entirely of cliffs cut in glacial drift, except where these are broken by the sand dunes blocking the former outlet of the Afon Soch. The high drift cliffs are flanked at either end of the bay by the great rocky headlands of Trwyn Talfarach in the west and Trwyn Cilan in the east. Both of these promontories are capped with glacial drift, and frequently the more gentle of their seaward slopes have thicknesses of similar material plastered over the rocks. Trwyn Talfarach is the seaward extension of a massive intrusion of hornblende-diorite which forms the eminences of Mynydd Penarfynydd and Creigiau Gwineu, and it was at the foot of the latter crag that a conglomerate was discovered which bore every resemblance to a raised beach deposit. The foreshore at this locality consists of massive blocks of hornblende-diorite similar to those which are scattered beneath the crags at a higher elevation. Consequently, these blocks are thought to have fallen from the cliffs of Creigiau Gwineu, possibly during the glacial period, but a diligent search failed to discover a wave-cut rock platform beneath this bulky debris. Behind and overlying this block material are unstable grass-covered slopes of glacial drift and hill-wash at the foot of which occurs the conglomerate, its landward extension obscured by slumped material (Plate 3B). It is about thirty feet in length, four feet in thickness, and its base is some three feet above high-water mark. The latter is somewhat difficult to distinguish on the rocky foreshore, but the upper limit of the *Fucus* Zone was taken as a line of demarcation (Plate 3B). The constituent rocks of the conglomerate are varied, and a petrological analysis distinguished the following: the smaller cobbles and pebbles consisted of dolerite, gabbro, quartz-felsite, rhyolite(?), greywacke, grit, limestone, greenstone-crush basalt and low grade slate. Although many of these are derived from the Pre-Cambrian and Ordovician series in Lleyn, there are several pebbles which are undoubtedly glacial erratics from North Britain. The water-smoothed larger cobbles and small boulders consist mainly of hornblende-diorite and are almost certainly derived from the local intrusion described above. In addition there is a variety of marine and terrestrial mollusca (Table I).

All these materials are cemented together by a matrix of calcareous tufa which also serves to fix the deposit to the underlying blocks of the foreshore. The matrix almost certainly derives from the boulder clay. The base of the conglomerate has been undercut and several blocks of it have become detached from the main mass. This undercutting may have resulted from the Romano–British transgression of which Godwin has found evidence in Southern Britain (Godwin, 1941), but since the deposit is so near to present high-water mark it may be the result of modern storm waves.

There was at first some doubt about the origin of the conglomerate for it bore a close resemblance to certain cemented gravels and calcreted sands which occur in the cliff face at both Nevin and Llanbedrog. These examples, however, are undoubtedly of fluvio-glacial origin, are unfossiliferous, and probably owe their cementation to percolating water highly charged with calcareous minerals from the overlying shelly drift.

It might be argued that the marine shells in the Porth Neigwl conglomerate were dredged from the floor of the Irish Sea by ice action, and therefore that the deposit is of glacial age, but an analysis of the Lleyn drifts shows that ice-dredged shells are usually so crushed and fragmented that they can only be distinguished under a microscope (Jehu, 1909). The mollusca of the Porth Neigwl conglomerate, on the other hand, are frequently preserved intact.

At this point it is important to establish the relationship which exists between the Porth Neigwl conglomerate and the raised beach platform of south-west Caernarvonshire.

TABLE I. **Mollusca from the Raised Beach, Porth Neigwl, Caernarvonshire**

MARINE SPECIES		TERRESTRIAL SPECIES
Type	Approximate Percentage of Species	
Littorina littorea	60%	*Helix aspersa*
Littorina littoralis	10%	*Oxychilus cellarius*
Littorina rudis	10%	*Retinella pura*
Nucella lapillus	10%	*Goniodiscus rotundatus*
Patella vulgata	10%	*Carychium minimum*

It is difficult to assess the spatial relationship which exists between the two, except on a basis of height above high-water mark, a criterion always regarded as a tentative means of comparison on its own. From such a comparison, however, it would appear that the base of the conglomerate lies some five feet below the average height of the Pre-Drift Raised Beach Platform. Three other important points emerge from the comparison: first, no wave-cut rock platform similar to that described above has been discovered anywhere in Porth Neigwl; secondly, an analysis of its fossil content indicates that the conglomerate is more likely to be of post-glacial age than of interglacial or pre-glacial age; thirdly, the drift which overlies the landward end of the conglomerate is undoubtedly a slumped deposit, alternately burying and re-exposing sections of the conglomerate (Plate 3B). Thus there is every possibility that the latter was formed as a beach at the foot of a boulder clay cliff in post-glacial times, and it cannot therefore be correlated with the Pre-Drift Raised Beach Platform. It is to be expected that if a remnant of an early post-glacial beach were to be preserved in

Porth Neigwl it would be found under the western slopes, most sheltered from the waves of maximum fetch.

The Porth Neigwl raised beach cannot be precisely dated in post-glacial time, and although raised beaches with a similar marine shell content have been described from the northern parts of the British Isles under various titles ('Littorina', 'Neolithic' and 'Early Post-Glacial') they are not necessarily contemporaneous. The O-isobase of the British post-glacial raised beach has been established in North Wales by Wright (1914, 1937) and his map has been widely adopted. Wright leaves no published record of the exact location in North Wales on which his map is based, and since there is a curious discrepancy in the position of the O-isobase between the first and the second editions of his book it is difficult to understand on what evidence this line is drawn. It is certainly of interest to the present study that the first edition indicates the Lleyn peninsula as being within the compass of the post-glacial raised beach, whilst in the second edition the whole of Lleyn is excluded. Finally, it is noteworthy that recent research points to a post-glacial strand-line of sixteen to seventeen feet O.D. in south-west Lancashire and Flintshire (Gresswell, 1953; Rowlands, 1955), which may be related to the Porth Neigwl raised beach.

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EXPLANATION OF PLATE 3

A. The Pre-Drift Raised Beach Platform at Porth Oer. Note how the platform bevels the top of the modern sea-stack.

B. The Post-Glacial Raised Beach in Porth Neigwl (Front elevation). Note the recent slumping of the drift which has obscured part of the conglomerate. The *Fucus* Zone can be distinguished as a dark colouring on the boulders in the foreground.

REFERENCES

Arkell, W. J. 1943. The Pleistocene Rocks at Trebetherick Point, North Cornwall. Their Interpretation and Correlation. *Proc. Geol. Ass., Lond.*, **54,** 141–70.

Charlesworth, J. K. 1929. The South Wales End-Moraine. *Quart. J. geol. Soc. Lond.*, **85,** 335–55.

Fearnsides, W. G. 1910. The Tremadoc Slates and Associated Rocks of South East Caernarvonshire. *Quart. J. geol. Soc. Lond.*, **66,** 142–88.

Godwin, H. 1941. Studies of the Post-Glacial History of British Vegetation. VI. Correlations in the Somerset Levels. *New Phytol.*, **40,** 2, 108–32.

GRESSWELL, R. K. 1953. *Sandy Shores in South Lancashire*. Liverpool.

JEHU, T. J. 1909. The Glacial Deposits of West Caernarvonshire. *Trans. roy. Soc. Edinb.*, **47**, 17–56.

JOHNSON, D. W. 1919. *Shore Processes and Shoreline Development*. New York.

MARTIN, S. 1955. Raised Beaches and their Relations to Glacial Drifts on the East Coast of Ireland. *Irish Geogr.*, **3**, 87–93.

MATLEY, C. A. & others. 1939. Summer Field Meeting in Western Lleyn. *Proc. Geol. Ass., Lond.*, **50**, 83–100.

MITCHELL, G. F. 1951. The Pleistocene Period in Ireland. *Dansk Geologisk Forenig*, **12**, 111–14.

ROWLANDS, B. M. 1955. 'The Glacial and Post-Glacial Geomorphological evolution of the landforms of the Vale of Clwyd.' Unpublished M.A. thesis, University of Liverpool.

STEPHENS, N. 1957. Some Observations on the 'Interglacial' Platform and the Early Post-Glacial Raised Beach on the East Coast of Ireland. *Proc. R. Irish Acad.*, **58**, B, 129–49.

——— & F. M. Synge. 1958. A Quaternary Succession at Sutton, Co. Dublin. *Proc. R. Irish Acad.*, **59**, B, 19–27.

WHITTOW, J. B. 1957. 'The Lleyn Peninsula, North Wales. A geomorphological study.' Unpublished Ph.D. thesis, University of Reading.

WRIGHT, W. B. 1914. *The Quaternary Ice Age*. 1st ed. London.

———. 1937. *The Quaternary Ice Age*. 2nd ed. London.

Great Chessells Gravel Pit near Bourton-on-the-Water, Glos, and the Occurrence of Mammalian Remains

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ABSTRACT: Patches of Jurassic river gravel near Bourton-on-the-Water, Glos, in the basin of the Windrush, have yielded mammoth and woolly rhinoceros. In their upper parts they display features associated with freeze and thaw. There is evidence for identification with the older gravels of the Summertown–Radley Terrace around Oxford and for recognising the stage from the headwaters of the Windrush to its confluence with the Upper Thames. Facts are given concerning bodies of clay in the gravel-bed, but their origin is obscure.

1. INTRODUCTION

IN THE Vale of Bourton are seven tracts of well-rolled limestone (or Jurassic) gravels, the boundaries of which are shown approximately on the Geological Survey maps, Sheets 217 (Drift) and 235 (Drift). Five of these tracts are in the northern part of the Vale in advance of where the Rivers Windrush, Eye (better known locally as the Slaughter Brook) and Dikler flow out of the hill country on to the, by comparison, low ground of the Vale. As would be expected, the gravel is composed almost entirely of pebbles of Inferior and Great Oolite limestones, the very small residue being of Liassic limestone, all of which were brought down by the rivers named.

Great Chessells Gravel Pit is situated on the north side of the Fosse Way immediately west of the Dikler at Stow Bridge between Stow-on-the-Wold and Bourton-on-the-Water. The original part of the pit, now worked out, was called Little Chessells Gravel Pit: the present vast pit is Great Chessells or Farnworth's Gravel Pit, after the name of the owner, Mr. L. J. Farnworth.

The pit has been kept under observation by Mrs. Helen O'Neil, F.S.A., for archaeological reasons, for over five-and-twenty years, and she has been rewarded by discoveries of great interest. It is very evident that this gravel tract was an occupation site during Romano–British times and possibly earlier. During this same period of over five-and-twenty years, ten molars of mammoth and four teeth of rhinoceros have been found and —except for one mammoth molar—have been presented to the University Museum, Oxford.

2. DESCRIPTION OF SECTION

The following is a very brief description of the section; details follow:

Surface-level. Maximum, *c.* 462 feet O.D.

	Thickness in feet
CLAY OCCURRENCES.	
LIMESTONE GRAVEL. Well rolled:	
1. *Festooned* ('frozen soil gravel') with highly inclined pebbles; no suggestion of soil: up to	3
2. *Fore-set*, with occasional lenses of ironstone pebbles and (*a*) of sandy clay, and (*b*) of oolith 'sand'. The teeth of mammoth and rhinoceros are said to have occurred consistently at the bottom of the face, i.e. at 9 or 10 feet above the Lower Lias: *c.*	10
——————— Pit floor, 1958 ———————	
3. *Bedded*, with numerous layers of greenish-yellow sandy clay: *c.*	9
Lower Lias. Tough bluish-grey clay.	

Secondary lime-cementation occurs, but it is not extensive. Ramifying veins of lime and lime-cemented gravel traverse the face from top to bottom.

The water-level fluctuates by five feet; but there is always a depth of two feet present, i.e. the maximum depth of water is seven feet.

The variation in depth of the present working-face is in accord with the contour of the ground. After the upper part of the gravel has been removed, it is contemplated removing the lower part, some nine feet thick; but, on account of its greater clay content, washing would probably be necessary.

3. CLAY OCCURRENCES

The Clay Occurrences are in two forms: (1) roughly, as a spread on the surface of the gravel; and (2) in pits—the 'clay-pits' of the quarrymen.

According to Mrs. O'Neil, the clay on the surface of the gravel is very generally distributed and reddish-brown in colour; but surface-appearances when seen by the authors indicated that much was blackish. The only place where the authors saw it clearly in section, capping the gravel, was along part of the western face of the pit. Here it is black and most likely the product of decalcification *plus* deep mixing of soil and organic matter due to the lengthy occupation of the site in Romano–British times and possibly earlier. From this stretch of clay were collected some Roman sherds, fragments of ironstone slag, and three small Bunter pebbles, one of which showed clear signs of having been used as a rubber. The junction of clay and underlying gravel is irregular; but no pipes involving the clay were observed running down into the gravel.

The ploughed fields on the limestones of the Cotswolds usually have a clayey soil, frequently reddish-brown on the Inferior Oolite, very sticky in wet weather. Mechanical analyses of six samples of soil on Inferior and Great Oolite limestones in the Cirencester district gave a silt-plus-clay percentage ranging from 44.7 to 56.2 (Hanley, *in* Richardson, 1933, 102). The Chessells gravel is pure limestone gravel (with the exception of ironstone pebbles, also derived from the local Inferior Oolite), devoid of quartzose sand, and, accordingly, very prone to decalcification.

It has not been found possible to make a satisfactory suggestion as to the origin of the 'clay-pits', but it appears desirable to give such facts as have been obtained.

An aerial photograph of the northern part of the gravel tract, the only part remaining unexploited at the time but now further reduced, showed a number of irregularly distributed white patches of various sizes and shapes. Mrs. O'Neil reports: 'We proved these white patches were "clay-pits" by watching three of them to see what happened.'

These clay-pits have been encountered all over the gravel tract and occur in the upper part of the gravel. The largest was one of the three mentioned above. To quote Mrs. O'Neil (*in litt.*, 16.9.58): 'Where I took the photograph it was thirty to forty feet across at the top. I did not measure the length as, of course, it was not uncovered all at once.' The clay was eight feet in depth and had normal gravel beneath.

The clay of this pit had been removed from its position in the gravel by the time of the authors' first visit, but they were shown the 'tip' and were thus able to examine it. It was mostly reddish-brown; was not blackened by deep mixing of soil and organic matter due to occupation; and was devoid of fossils (which might have dated it, geologically) and fragments of pottery, bones and charcoal. According to Mrs. O'Neil (*in litt.*, 11.9.58): 'These clay areas did not produce any finds, and, in fact, where any Romano–British hut or house site impinged on a clay-pit, the foundations of the hut or house were reinforced with extra stone revetments.' The clay contained, however, flattish pebbles of ironstone similar to those concentrated in the lenses in the gravel and sporadically distributed elsewhere. One medium-sized Bunter pebble was obtained from the clay.

The last pit brought to light (August 1958) was examined by one of the authors (K.S.S.); but only to a depth of, say, two and a half feet, because evidence obtained appeared to indicate that the clay-pit was artificial, and,

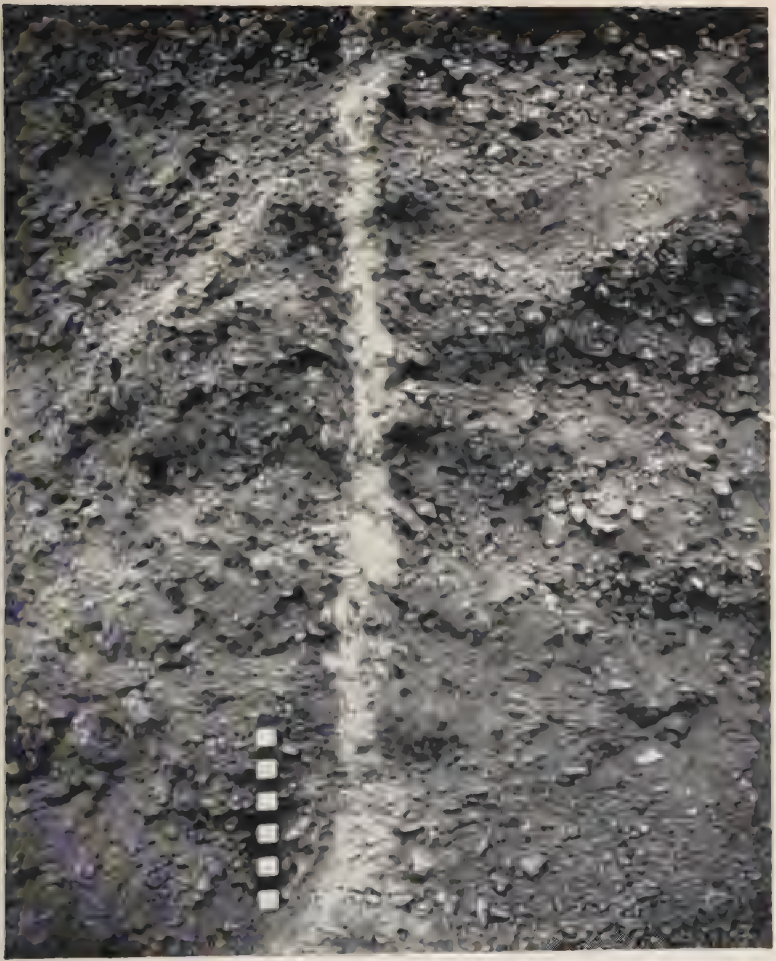

Photo: *Mrs. Helen O'Neil*

One of the many lime-pipes in the gravel at Great Chessells Gravel Pit

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consequently, the concern of the archaeologist rather than the geologist. It was about eight feet in diameter and the junction of clay and gravel was sharp. At about two feet down some flat slabs of limestone were encountered, beneath which was similar clay again. In the top of this clay, just beneath the limestone slabs, a piece of red pottery and a flint were found. Mrs. O'Neil has pronounced the pottery Roman; and the flint a chip off a pebble—not an artefact.

Concerning this last clay-pit, Mrs. O'Neil remarks that it certainly does seem to have a very clear-cut edge; but adds that the enormous clay-pits she had previously reported were certainly natural.

One of the authors (L.R.) favours the opinion that the clay-pits are natural, but is unable to make a satisfactory suggestion as to their origin. It is noteworthy that the clay lacks the blackish colour and archaeological contents due to the occupation of the site. It contains, however, numerous flattish ironstone pebbles similar to those in the gravel-bed. It may be recalled that in clay occurrences in gravel acknowledged to be the product of decalcification the limestone pebbles have been removed, while those of ironstone have survived.

4. THE GRAVEL

The gravel, as has been already stated, is limestone gravel composed almost entirely of pebbles made of rock derived from the Inferior and Great Oolites of the neighbouring hills. Flattish pebbles of the sandy form of Cotswold (or Stonesfield) Slate are numerous. So far as is known the Stonesfield Slate beds do not occur in the hills bordering the Dikler valley in the neighbourhood of the Swells, but they are present and well developed in the hills west of Upper Slaughter and on Eyford Hill on the west side of the River Eye. Pebbles of bluish-grey Lias limestone occur, but are few. Those of ironstone, however, are frequent, and largely compose lenses in the Fore-set Gravel. On account of their black colour they quickly catch the eye. These ironstone pebbles, mostly on the flattish side, were doubtless derived from such 'Very ferruginous . . . beds, full of ossicles of *Isocrinus* and fragments of echinoid radioles', as constitute the top part of the Pea-Grit Series Equivalent in the—now long-disused—Town Quarry near Copse Hill House, a mile or so to the north-west of Chessells (Richardson, 1929, 60).

The Festooned Gravel (1 of section, p. 41) includes a considerable amount of marly matter, the result of decalcification—a process still active.

The Fore-set part of the gravel deposit contains occasional lenses of (*a*) greenish-yellow clay with an admixture of fine-grained sand, and (*b*) of 'sand', not quartzose, but composed entirely of loose ooliths. No fresh-water shells have been detected in the clay lenses.

The Bedded Gravel has not yet been worked in this pit, but it has been partly exposed in a trial trench and is still well-exposed in Young's old gravel-pit adjoining Chessells on the south-west and now owned by Mr. A. T. Wheeler of Lower Slaughter. This Bedded Gravel has numerous layers of greenish-yellow sandy clay intercalated.

Secondary lime-cementation of the gravel has been observed in most of the pits once open in the neighbourhood; but it is not much in evidence in the part of the gravel exposed in this pit. Ramifying veins of lime and lime-cemented gravel locally descend the working-face from top to bottom and are more recent than the festooning of gravel.

A feature of the eastern face, which is much lower than the western owing to the slope of the ground towards the Dikler, is the number of pipes that in vertical section give the impression of being thin partitions of gravel in the main mass. Their sides are plumb and apparently devoid of clay lining, are up to four inches in diameter, and have their contained pebbles with their longer axes vertical. In places as noticed by Dines (*in* Richardson, 1946, 114) in the case of pipes in the terrace at Long Hanborough, the bedding adjacent the pipe is, in places, turned upwards. No pipes, such as those that make so marked a feature of the Hanborough Terrace, have been developed in the Chessells gravel.

Pebbles of rock foreign to the district are extremely rare in the gravel: A. E. Salter failed to find any (Salter, 1905, 37), and Mrs. O'Neil has only come across one small one—a 'Bunter' pebble. She has never found a flint *in* the gravel; but, on the occasion of a visit of the Geologists' Association to one of the local pits in 1904, at a time when it was customary to search most carefully for flints in the Cotswold limestone-gravels, one small piece was found *in situ* (Richardson, 1904, 412).

5. MAMMALIAN REMAINS

The only previously published records of mammalian remains from the Vale of Bourton are by W. C. Lucy (1869, 123) and C. I. Gardiner (1939, 329). Lucy's record is a 'Tusk from near Bourton-on-the-Water'. Gardiner's records are a tooth of rhinoceros and three teeth of mammoth (identified by one of us (K.S.S.) as 'essentially of the *Elephas primigenius* stock', now in the Stroud Museum) from the now-disused Young's Gravel Pit; and one of mammoth from a pit nearer Bourton—by the side of the road to Bourton shortly after it has left the Fosse Way.

In the Gloucester Museum are two specimens of *Elephas primigenius*, the one from Great Chessells Gravel Pit (Reg. No. 107/1957); and the other (16,881) found when sinking a well in the gravel-bed in Church Field, Bourton-on-the-Water, in 1910.

The nine mammoth teeth from the Great Chessells Gravel Pit in the University Museum, Oxford, may be described summarily as follows. One has a black-mottled white outer surface and came, probably, from a distinctive bed in the gravel, the remainder have almost identical yellowish and yellowish-brown surfaces: recent fractures are white. Four upper and three lower molars are represented, but none is complete. One specimen is probably part of an ultimate molar, the rest are probably later milk molars and early molars. The lamellae have notably strong, rather thick, crimped enamel and interlamellar cement is well developed (a condition which is variable with the height and other conditions of the tooth). Lamellar frequency (i.e. the number of plates within 100 mm.) is about ten. No tooth is complete enough for the lamellar ratio to be assessed with any satisfaction. In their features, however, the teeth are certainly like those of *Elephas primigenius* known from the Summertown–Radley gravels around Oxford (Sandford, 1925), and unlike those from the later, Flood Plain, gravels there.

Three distinctive upper molars, and one lower molar, may be referred to the woolly rhinoceros (*Rhinoceros tichorhinus*), and they have the same external coloration as the mammoth teeth [K.S.S.].

6. CORRELATION OF GRAVEL

The gravels described in this paper are isolated in the headwaters of a tributary of the Windrush. Farther downstream the main river flows in a spectacular Cotswold valley almost entirely lacking patches of old gravels, though the well-known abandoned meander and prominent meander-core at Asthall indicate a stage of valley deepening. The morphological features of the basin within the Cotswolds have been described by Beckinsale & Smith (1953), and it is hoped that further work will be done on the benches within the main valley as far as Witney. Here the Windrush passes on to the Oxford Clay plain and its gravels (with those of the adjacent Upper Thames) are widespread (Pringle & others, 1926; Richardson & others, 1946). Those referred to the Summertown–Radley terrace around Oxford (Sandford, *in* Pringle & others, 1926) predominate and contain mammoth and woolly rhinoceros: an upper, unconformable series seen locally upon them contain a fauna characterised by hippopotamus and *Elephas antiquus*. Frost-disturbed layers occur there near the top of whichever gravel forms the terrace-surface, i.e. the disturbed condition may have been attained either after the lower (mammoth) gravels were formed or during a cold period after the upper (hippopotamus) beds were formed. The geology of the deposits indicates that the latter is correct, but it is not to be assumed that there was only one such time of disturbance. In the writer's experience similar features do not occur on the superficial part of the Flood Plain gravels.

Though the gravels of Great Chessells form a clearly marked terrace feature beside the Dikler, their base is but little above it, and probably, as in some places around Oxford, thickening occurs toward the stream. In their disposition they recall the gravels of the Summertown–Radley stage: the only fauna associated with them—and that derived from their upper part—is that of mammoth: the disturbance of their uppermost part is two-fold (p. 44), and hippopotamus-gravels are lacking. It is considered, therefore, that the stage is represented in the Windrush basin from the headwaters, through the Asthall meander, to the confluence with the Upper Thames [K.S.S.].

ACKNOWLEDGMENTS

The 'finds' both archaeological and geological are largely due to the active co-operation of Mrs. O'Neil, Messrs. T. O., L. J. and T. Farnworth and the quarrymen, particularly Mr. C. L. Holford. Geological circles are indebted to Mrs. O'Neil for collecting, preserving and eventually handing over the teeth for study and safe keeping. We would also record our thanks to Dr. R. P. Beckinsale for much help during our investigations.

REFERENCES

Beckinsale, R. P. & K. W. Smith. 1955. Some Morphological Features of the Valleys of the North Cotswolds: The Windrush and its Tributaries. *Proc. Cotteswold Nat. Fld Cl.*, **31**, 184–95.

Gardiner, C. I. 1939. Rhinoceros Tooth. *Proc. Cotteswold Nat. Fld Cl.*, **26**, 329.

Lucy, W. C. 1869. The Gravels of the Severn, Avon and Evenlode, and their Extension over the Cotteswold Hills. *Proc. Cotteswold Nat. Fld Cl.* **5**, 71–125.

Pringle, J., *et al.* 1926. The Geology of the Country around Oxford (2nd ed.). *Mem. geol. Surv. U.K.*

Richardson, L. 1904. Excursion to . . . the North Cotteswolds. *Proc. Geol. Ass., Lond.*, **18**, 391–408.

——— *et al.* 1929. The Country around Moreton-in-Marsh. *Mem. geol. Surv. U.K.*

——— *et al.* 1933. The Country around Cirencester. *Mem. geol. Surv. U.K.*

——— *et al.* 1946. The Geology of the Country around Witney. *Mem. geol. Surv. U.K.*

Salter, A. E. 1905. On the Superficial Deposits of Central and Parts of Southern England. *Proc. Geol. Ass., Lond.*, **19.**

Sandford, K. S. 1925. The Fossil Elephants of the Upper Thames Basin. *Quart. J. geol. Soc. Lond.*, **81**, 62–86.

The White Lias of the Devon Coast

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ABSTRACT: The White Lias of the Devon coast consists of a series of poorly fossiliferous calcilutites separated by thin partings of marl. Structures include intraformational conglomerates, sun cracks, corrugated and stained surfaces, wedge bedding and slump phenomena. Two faunal groups are recognised, a community of benthonic molluscs and corals and a community of burrowing and perhaps boring organisms.

Comparison is made with the Bahaman drewite deposits. The White Lias was similarly deposited in warm water, in a shallow lagoonal marine environment. The mollusc-coral community was more or less confined to areas of hard substratum while the burrowing community probably characterised the intertidal zone. Besides periodic warping and slumping the beds were subjected to regular minor oscillations of sea-level, which caused periodic emergence, rapid consolidation and subaerial erosion of limestone. Subsidence into deeper waters, where more argillaceous deposits were forming, accounts for the occurrence of marl partings.

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1. INTRODUCTION

THE WHITE LIAS is a well-known formation clearly distinguished from the Rhaetic shales below and the Blue Lias above by a characteristic development of poorly fossiliferous, whitish fine-grained limestones. Doubt remains whether it is better classified with the Rhaetic or the Lias; at present it is regarded as forming part of the Upper Rhaetic and has been termed the Langport Beds (Arkell, 1933).

Incomparably the best exposed section in the country occurs in the cliffs of Pinhay Bay, Devon, one and a half miles west of Lyme Regis and readily accessible to the geologist. It is all the more surprising, therefore, that the section has received but scant attention in the literature. Richardson, who is responsible for the most recent comprehensive account of the Rhaetic in Devon (1906), described it only briefly. His standard section was drawn up for comparable but more poorly exposed beds on the west side of Charton

Bay, one and a half miles to the west, where, however, the complete Rhaetic sequence can be studied. Yet there are a number of sedimentary structures at Pinhay Bay which have an interest out of all proportion to the small thickness of the beds concerned. In this paper an attempt is made to describe these features and to interpret them in the light of knowledge of similar deposits forming at the present day. Although only Pinhay Bay receives detailed attention, consideration is given where necessary to the only other good exposures in the area, at Charton Bay and at Tolcis, near Axminster, seven miles inland.

2. DESCRIPTION OF THE WHITE LIAS

(a) Section at Pinhay Bay

The individual beds are highly variable within short distances due both to change of lithology and to wedging out. Therefore only a generalised section can be given, but this will suffice for present purposes. The beds are nearly horizontal but eastwards the Blue Lias descends gradually to the base of the cliffs. The position of the outcrops in the cliffs and on the shore can be found from the 25 inch-to-the-mile map of Lang (1924).

	ft.	in.
Langport Beds (White Lias). Pale grey limestones, weathering generally to a cream colour, with partings of marl	25	9
14. Sun Bed. Limestone, locally a conglomerate with limestone pebbles in a marly matrix; thickens locally. *Rhizocorallium parallelum* (Torell)	0	2
13. Thin limestones with slightly irregular surfaces and partings of brown marl; some are rubbly or have perforated upper surfaces. *Modiolus langportensis* (Richardson & Tutcher) ...	1	4
12. Limestone with locally an irregular upper surface: occurs only in east; replaced westwards by several thin limestones ...	0	10
11. Thin rubbly limestones with irregular marl partings; shelly band near top. *Liostrea irregularis* var. *hisingeri* (Nilsson), *Modiolus langportensis*, *Montlivaltia* sp.	0	9
10. Shelly marl with lenticles of limestone. *Atreta intusstriata* (Emmrich), *Liostrea irregularis* var. *hisingeri*, *Modiolus langportensis*, *Parallelodon hettangiensis* (Terquem), *Pleuromya* sp., ? *Protocardia* sp., small gastropods	0	1
9. Limestone, locally porcellanous, with perforated top	0	4
8. Main Slump Bed	4	6
7. Porcellanous limestone	0	2
6. Thin, rubbly limestones with irregular marl partings and pockets of small molluscs. *Chlamys valoniensis* (Defrance), *Lima* cf. *gigantea* (J. Sowerby), *Isocyprina ewaldi* (Bornemann), ? *Nuculana* sp., *Parallelodon hettangiensis*, *Protocardia phillipiana* (Dunker), *Montlivaltia* sp.	2	10
5. Limestone with irregular base	0	8

	ft.	in.
4. Limestone, locally with a rubbly top, containing numerous subangular fragments of porcellanous limestone; minor slump structures	4	6
3. Thin limestones. *Isocyprina ewaldi*, *Lima* cf. *gigantea*, *Protocardia phillipiana*	1	8
2. Limestone with minor slump structures and locally a porcellanous top	1	11
1. Thin limestones locally becoming porcellanous and rubbly, with slightly irregular surfaces and partings of marl up to one half inch thick; rare pockets of small molluscs	6	0

(b) Petrology and Chemistry

Two sorts of limestone can readily be distinguished by the naked eye. The first and commoner variety is generally pale cream or yellow in colour, tends to have a dusty surface and is never porcellanous. The other variety is pale grey in colour, has a clean surface and is characteristically porcellanous, though perhaps rougher textured than the familiar Carboniferous varieties. The mutual relations of the two varieties are most interesting. The porcellanous limestone occurs as thin selvages, up to three-quarters of an inch thick, on beds of the ordinary type, either on the upper surface alone, if the bed is thick (e.g. bed 2), or typically on both upper and lower surfaces. It also occurs as thin bands up to about four inches thick. Where a porcellanous band thickens laterally a core of ordinary limestone develops. These relationships are illustrated in Fig. 1. A further point of difference is that the subangular fragments of rubble are almost invariably porcellanous whereas only the other sort shows deformational structures. There is a trace of fine lamination on the weathered surfaces of a few porcellanous bands.

As seen in thin section all the limestones are composed of a fine homogeneous mosaic of interlocking calcite crystals ranging between 0.002 and 0.200 mm. and averaging about 0.010 mm. in diameter. They may most usefully be classified as calcilutites *sensu lato*, i.e. with grain size ranging from clay to silt grade. Though it might reasonably be expected that the porcellanous limestones would be finer grained than the ordinary types, no such distinction can be made under the microscope.

Tiny, irregularly shaped fragments of carbonaceous matter ranging up to 0.090 mm. and granules of pyrite (in fresh rock) averaging 0.001 mm. and ranging up to 0.025 mm. vary in abundance from rare to moderately common. There is a singular absence of recognisable calcareous organic fragments in all the slides examined. Detrital quartz, of silt grade, is also very rare.

The limestones are very pure. Analyses of the percentage of material insoluble in cold 10% HCl gave, for two samples of (a) porcellanous limestone, 2.43 and 1.83% and (b) ordinary limestone, 4.00 and 2.87%.

These analyses suggest that the ordinary limestone is a little more decalcified than the porcellanous, presumably due to weathering. The amount of insoluble residue in a sample of blue-grey marl from bed 10 was estimated to be 45.66%. An analysis of the carbonate fraction of one specimen of limestone showed it to consist almost entirely of $CaCO_3$, with $MgCO_3$ less than 2%.

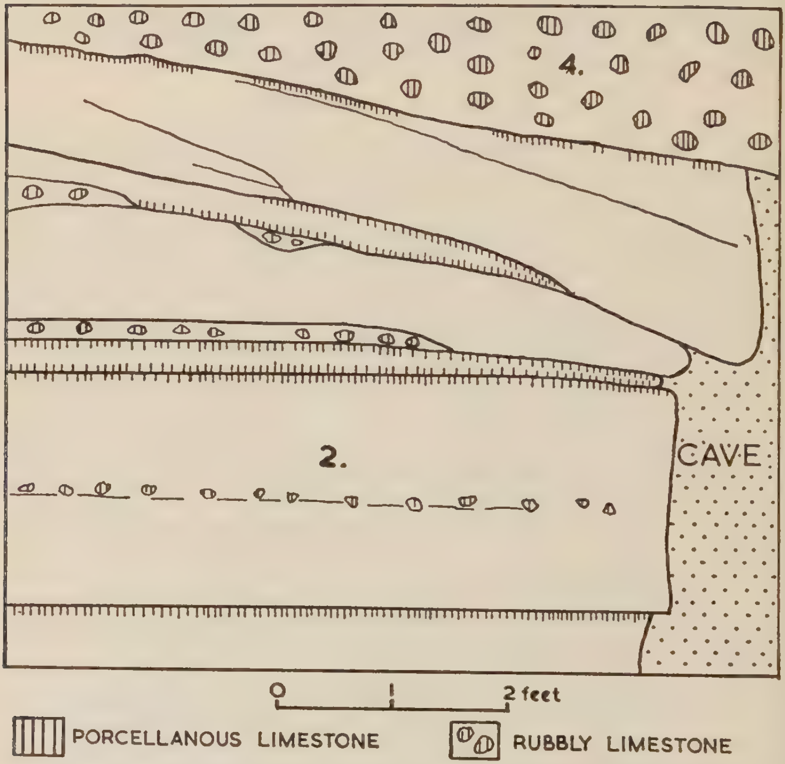


Fig. 1. Diagram of a section on the west side of Pinhay Bay, showing wedge bedding, rubbly limestones and porcellanous selvages. The numbers refer to beds in the section described in the text

Analyses of strontium content of the carbonate fraction of three limestones were kindly undertaken for the writer by Mr. R. Allen, as part of a general programme involving carbonate sediments of all ages. It has become customary to express the strontium content as the ratio Atoms Sr/Atoms Ca × 1000. In making this calculation for the White Lias samples the carbonate has, for convenience, been assumed to consist entirely of $CaCO_3$. Two of the samples gave values of 10.0 for the ratio, the third 2.0. These results are striking, for they are far in excess of the mean for limestones of different ages given by Kulp, Turekian & Boyd (1952), the first two by a factor of 14. A consistent error overestimating strontium in these analyses can be ruled out since the mean for the other limestones in the series is actually less than that given by Kulp, Turekian & Boyd.

Such a high strontium content strongly suggests deposition as aragonite of the original lime mud for, however enriched the sea-water was in this element, the content in the limestones appears to be much greater than could be accommodated in the calcite lattice. It is surprising that the White Lias rocks should have retained so much strontium, for normally when aragonite is transformed into calcite during diagenesis the strontium content drops considerably (Revelle & Fairbridge, 1957). Presumably the strontium is retained in strontianite.

(c) Structures

(*i*) *Intraformational Conglomerates.* At most horizons thin beds occur with local aggregations of angular or subangular limestone pebbles, giving rise to a rubbly rock. These pebbles are sometimes more or less spread out as layers, sometimes they are distributed locally in pockets. Their maximum diameter rarely exceeds 5 cm. Bed 4 is particularly striking and was mentioned by Richardson (1906). Unlike in the other beds the pebbles are distributed through several feet of rock (Plate 5C). They are commonest near the easternmost exposure of the bed, towards the centre of the bay, where they extend through some three feet vertically. Westwards, however, the numbers dwindle rapidly.

(*ii*) *The Limestone Surfaces.* It has long been recognised that phenomena indicative of emergence above sea-level, such as sun cracks and bored surfaces, are present in Pinhay Bay and so especial attention was paid to the limestone surfaces. Those of the top seven beds are exposed on the foreshore at low tide.

What appear to be true sun cracks have been recognised only in the top bed (the Sun Bed). The polygons produced by the cracks are five to seven centimetres in diameter and are well exposed on the foreshore in the middle of the bay. Laterally the bed passes into an intraformational conglomerate owing to the break-up of the polygons.

Perforations in the rocks are common throughout the succession. Whether or not they represent borings is discussed in the section dealing with the fauna.

The surfaces of the beds on the foreshore generally have a prominent red stain due to the oxidation of pyrite. That this is caused by penecontemporaneous weathering is suggested by the total lack of such stains throughout the overlying Lower Lias beds outcropping on the foreshore although most of them contain abundant pyrite.

The junctions of the lower group of limestones are sometimes serrated in a manner at first suggestive of stylolites as, for instance, described by Stockdale (1926). They differ from typical stylolites, however, in several respects. In the first place the irregularities are comparatively slight and lack the characteristic closely spaced and sharply acute peaks and troughs. Further, the marl partings, far from being mere films of microscopic thickness, do not differ apparently from those between regular limestone surfaces, into which indeed they may pass. If, as generally accepted, stylolite marl partings are residual in origin they should be thicker the more extreme the serration. Finally, the serrated top of a bed might also be porcellanous. There seems to be nothing to oppose the suggestion that the tops of certain limestone beds were corroded and that the succeeding beds accommodated themselves to the troughs and peaks of the corrugated surfaces.

(*iii*) *Wedge Bedding*. This is fairly common throughout. It is particularly well shown in bed 3, in which the limestones wedge out both to the north-west and south-east (Fig. 1).

(*iv*) *Slump Structures*. Perhaps the most striking individual feature in Pinhay Bay is the Slump Bed (8) which is a magnificent example of its kind. Its thickness remains constant at between four and a half and five and a half feet. Close examination can be made in the extreme easternmost exposures of the White Lias, in the caves towards the middle of the bay and in a fallen block in the west, near Pinhay Steps.

The bed contains large detached masses of contorted limestone and scattered, small subangular fragments of porcellanous limestone in a limestone matrix. Some of the larger inclusions are visibly detached fragments of folded beds, with folds up to 180° (Fig. 2b). Others are in the form of crudely spheroidal bodies (slump balls) up to six feet in diameter. Some particularly fine examples of these occur in the middle of the bay (Plate 5B). Thin marly streaks in the limestone reveal highly complex small-scale contortions (Plate 5 A). Some inclusions are suggestive of a plastic 'pinching out' (Fig. 2a). All the inclusions are coated with a film of brown marl. As far as can be ascertained without a thorough statistical investigation orientation of the structures is random.

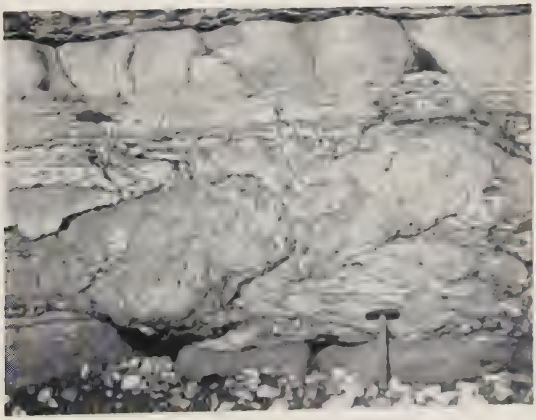
There is a constant basement bed consisting of a band of porcellanous limestone generally about two inches thick. Followed westwards, it thickens to five inches in the middle of the bay and passes into ordinary limestone a few yards west of the western cave and is here overlain by a bed of ordinary limestone eleven inches thick, which continues west for a few tens of yards before wedging out abruptly. In the extreme west the porcellanous band is again present. It is generally overlain immediately by a concentration of angular porcellanous fragments never more than two inches thick and up to seven inches long.

C

Pebble bed (number 4 in succession)

B

Slump bed, showing slump balls



A

Slump bed

[*To face p.* 52

The upper surface of the Slump Bed has truncated structures and organic perforations, as seen in the east. The surface exposed on the foreshore reef is hummocky. It is overlain by a bed of limestone (9), sometimes porcellanous, which thickens locally up to eight inches and fills in hollows of the surface below.

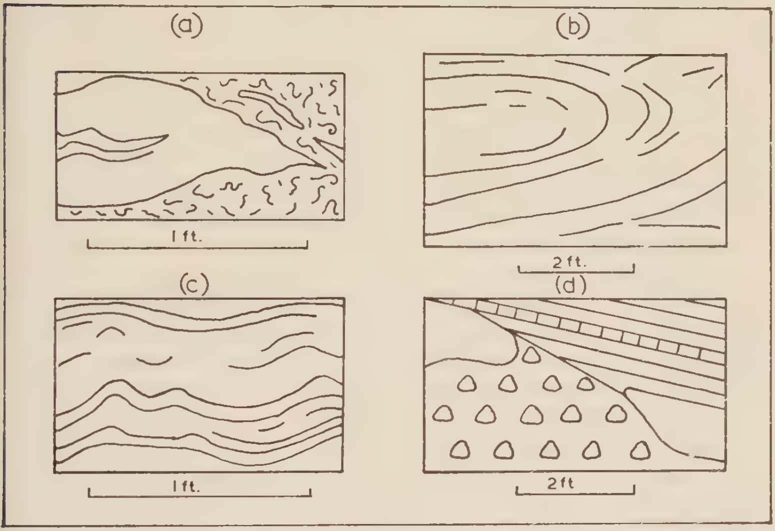


Fig. 2. Diagram illustrating contemporaneous deformational structures in the White Lias: (a) part of a folded limestone bed in the Slump Bed, Pinhay Bay, the core of which has been plastically squeezed and tapers to a point; (b) part of a limestone bed within the Slump Bed which has been folded on itself as in (a); (c) minor contortions, including pseudo-ripple marks, near the base of the section in Pinhay Bay; (d) normal fault at the horizon of the Broken Beds, Charton Bay, showing breccia material underlying the fractured limestone. The younger beds pass undisturbed over the fault

The various structures described, namely the slump balls, the detached, randomly arranged folded masses, the minor contortions and the truncated top, can all be matched with slump structures in the Welsh Palaeozoic described by Jones (1937) and Kuenen (1948). The thickness and lateral constancy of the bed compare closely with the structures Kuenen studied. The only other British record of slumping in limestones known to the writer is that of Dunnington (1945), who described disturbances in the Carboniferous of the Skipton area.

There is an obvious interest in the lateral extent of the Slump Bed, as far as it can be ascertained. On the west side of Charton Bay the following section was measured in a fault block of Rhaetic and Lias beds at the foot of the cliffs, close to the Cretaceous.

	ft.	in.
8. Blue Lias shale		
7. Fairly regular limestone	0	9
6. Marl with limestone lenticles	0	1
5. Fairly regular limestone	1	0
4. Group of nine thin-bedded limestones	1	1
3. Broken Beds	3	11
2. Porcellanous limestone	0	1½
1. Rubbly limestone	0	4+

The Broken Beds at the west of the exposure have a top bed of massive limestone seven to fourteen inches thick, which is underlain variously by breccia (porcellanous fragments) and more or less massive limestone. Bedding in this upper part is obscure. The lower part of the Broken Beds here consist of thin-bedded limestones, locally rubbly, about one foot four inches thick. In the eastern part of the section is an intraformational fault associated with breccia (Fig. 2d).

The existence of these Broken Beds is most illuminating, for they occur at the same horizon as the Slump Bed, which has virtually the same thickness, and even have what is presumably the same distinctive basement bed. Deformation here, however, is due essentially to fracture of material *in situ*.

In the quarry at Tolcis, near Axminster (177/280010), there is no trace of any slump or fracture phenomena.

Evidence of contemporaneous plastic disturbance is present in several other beds at Pinhay Bay, notably beds 2 and 4. It reveals itself by undulating bedding planes, marked out by marl seams. A recently slipped block next to Pinhay Steps Fault in the west shows some particularly fine small-scale folds (Fig. 2c) with a north-west–south-east strike. Folds in bed 12 have a north–south strike. Some of the folds have sharp crests and amplitudes similar to small-scale ripple marks and presumably it was these that Richardson indeed identified as ripple marks (1906, 407). Kuenen has in fact termed such structures pseudo-ripple marks (1948, 372); the 'wavy bedding' described from limestones in the Permian of Texas looks similar (Newell *et al.*, 1953, 80).

(*v*) *Post-White Lias Faults*. A number of small, high angle faults with a throw of several inches pass upward, in some cases at least, into the Blue Lias, which they plastically deform. They are probably all post-White Lias in age and so have no bearing on the conditions of deposition; they are not further considered here, beyond the observation that the top beds of the White Lias must have been consolidated before deposition of the Blue Lias.

(d) Fauna

Two distinct faunal communities are recognisable.

(*i*) A community of pelecypods and gastropods with a few solitary corals. They tend to occur locally at certain levels as tightly packed clusters of small shells up to a yard or so in area but rarely more than an inch thick. The dominant fossil is *Protocardia phillipiana* (Dunker). The shells of this form cover a wide size range and are invariably found with the two valves together. They are more or less confined to the thin-bedded limestones. There can be little doubt that they represent original associations.

The marl (10) is exceptional in containing abundant oysters and *Modiolus* which, moreover, are more or less uniformly scattered throughout the bed. *M. langportensis* (Richardson & Tutcher) is the dominant form in the top beds of the White Lias in the Tolcis quarry, where it occurs in abundance at several levels, the shells evenly distributed but with valves united. This faunal difference is correlated with a slight difference in lithology, the marl/limestone ratio being higher (Hallam, 1957).

(*ii*) Communities of burrowing and perhaps boring organisms. These were common and left traces throughout the succession. The Sun Bed is riddled with the U-shaped burrows of the trace-fossil *Rhizocorallium*, described by Richter (1926), which have a characteristic median septum or 'Spreite'. They were produced by sediment-feeding organisms (A. Seilacher, personal communication), probably some variety of worm or crustacean. They are best seen in the Charton Bay section; on the Pinhay Bay foreshore truncation of the tops of the burrows indicates that some two inches of the Sun Bed have been removed by erosion. A striking feature of these structures is that they are surrounded by a zone of bleached rock some quarter of an inch thick which is itself surrounded by a dark band up to one twelfth of an inch thick. Microscopic examination reveals that these differences are due to the uneven distribution of pyrite granules; they are absent from the bleached zone and concentrated in the dark zone. The suggested explanation is as follows. Perhaps but not necessarily during the decay of the organism sulphurous fluids migrated into the rock. Pyrite granules were dissolved and the solution progressively concentrated until, at a certain distance from the burrow, the solubility product of FeS_2 was exceeded and the mineral rapidly precipitated, giving a dark band. This process is essentially comparable to the phenomenon of gleying in soils.

Two other types of structure occur, both of which can be studied at the top of bed 8. The first type also consists of U-shaped burrows but much smaller than those just described. The maximum dimensions are 2.5 and 1.0 cm., with a tube diameter of up to 0.2 cm. They were probably inhabited by a different species of organism. The others consist of more or less straight tubes, up to 1.2 cm. in diameter, which run oblique to the surface and sometimes coalesce. The identity of the organisms responsible for these structures is doubtful but the most likely agents are decapod crustaceans or worms. In both cases a peripheral bleached zone has been observed. The marl infillings have weathered out in most cases, leaving distinct perforations in the rock. Observations by the writer on trace-fossils in the Blue Lias suggest that the White Lias limestones were probably consolidated before the perforations were infilled by marl, because there is no evidence of a migration of $CaCO_3$ from limestone to marl, effecting a local hardening of the latter, as is the case in these younger rocks. It is difficult to decide, however, whether some of the perforations represent borings into hard rock or burrows made in mud which was subsequently consolidated before the renewal of sedimentation. In the case of the *Rhizocorallium* structures there is no doubt—they must have been excavated in soft sediment.

3. COMPARISON WITH THE GREAT BAHAMA BANK

Illuminating comparisons can be made with the well-known aragonite muds (drewite) in the protected, very shallow water shelf lagoons west of Andros and Abaco Islands in the Bahamas (*see* Illing, 1954 and Newell, 1955 for general accounts of the Bahaman sediments and lists of references). Though it is widely accepted that the tiny aragonite crystals were precipitated directly from sea water (Smith, 1940) it is possible that they consist of the disintegrated remains of algae washed into the area (Lowenstam & Epstein, 1957). The White Lias limestones, with their similar chemical composition, most notably in strontium content, were almost certainly deposited in warm, shallow water as aragonite mud, though the present microfabrics indicate complete diagenetic recrystallisation to calcite. The presence of corals suggests a marine environment.

On the west coast of Andros fragments of partly consolidated drewite are eroded from the low cliffs and swept into the submarine muds to form intraformational conglomerates (Black, 1930; Field *et al.*, 1931); without much doubt the White Lias conglomerates were formed in a similar way. According to Illing, sediments raised above sea-level are rapidly consolidated into limestone by recrystallisation. The oolitic cay rock on the islands within reach of sea spray is strongly corroded due to irregular solution of carbonate, giving rise to corrugated surfaces (Illing, 1954, 50), which may be likened to those in the White Lias.

The puzzling relationships of the two types of White Lias limestone can perhaps be most satisfactorily explained by differences in the speed of consolidation. If soft calcareous mud be raised above sea-level and warmed by the sun CO_2 will quickly be given off and the consequent raising of pH in the interstitial waters will initiate precipitation of $CaCO_3$. Rapid recrystallisation will ensue, leading to the formation of a hard limestone. It might reasonably be assumed that rapid consolidation of this sort produces a porcellanous rock. The surfaces of an uplifted bed should be the quickest to consolidate and thin beds should consolidate more rapidly than thick ones. The occurrence of porcellanous limestone as selvages and as thin bands may thus be accounted for. The overwhelming dominance of porcellanous limestone in the rubble derived from the break-up of more or less brittle limestones and the plastic behaviour of the ordinary limestone under contemporary stresses is also accounted for. An unsolved problem concerns the apparently greater susceptibility to weathering of the ordinary limestone. Perhaps the porcellanous limestone is more compact, i.e. less porous.

Generally speaking, the Bahaman mud environment appears to be inimical to benthonic organisms, which are abundant only where small patches of hard rock occur (Black, 1933). Significantly, the mollusc-coral community in the White Lias is confined to thin limestone groups where, it may be supposed, they settled on patches of firm bottom. Mr. M. Black, with personal knowledge of the Bahaman muds, considers the intertidal zone to be the likeliest environment for the burrowing organisms (personal communication). The burrowing community may therefore signify a more emergent phase in the history of a given sediment.

4. CONTEMPORARY DISTURBANCES

(a) Slumping

The plastic sediments were periodically deformed by disturbances on the sea-bed. When these disturbances were slight they caused little more than crumpling of the strata due most likely to small movements down a gentle slope under the influence of gravity. It was, however, an intense disturbance which gave rise to the Slump Bed. Strata were not merely crumpled. They were intensely twisted and contorted, lumps torn off and incorporated into the moving mass. A snowball effect due to rolling converted some of these plastic masses into huge balls. At the same time thin beds of brittle limestone were shattered, the interstratified marl squeezed out and the broken fragments intimately mixed with the dough-like bodies rather like sultanas in a suet pudding. The mobile slump sheet did not plough down into the underlying sediments but rode over a thin bed of brittle, porcellanous limestone which acted as a sole. Parts of this sole were broken off and incorporated into the base of the moving mass. Beds at the same horizon in Charton Bay reacted to the initial stresses essentially by fracturing *in situ*. It follows that they were at least partly consolidated at the time. The slope on which slumping was initiated need never have exceeded 1° (Kuenen, 1948). It was produced probably by tectonic warping. Warping also provides an explanation for the wedge bedding that has been described. A bed would wedge out up a slope approaching a low island. An overlying bed wedging out in a different direction implies subsequent warping excepting the case in which two wedge beds are complementary to each other. The structure of the wedge bedding illustrated in Fig. 1, in which the wedges are convex downwards, is difficult to account for unless some subsequent plastic deformation is invoked. The formation of the Slump Bed and also probably the intraformational folds required the brief application of a violent stress; earthquakes would seem to provide the likeliest trigger mechanism.

(b) Sea-Level Oscillations

The sun cracks, intraformational conglomerates, corrugated and reddened surfaces, animal burrows and borings(?) and the various lines of evidence signifying rapid consolidation of limestone provide good evidence that islands periodically rose above sea-level. The renewal of sedimentation just as clearly signifies subsequent submergence. Knowledge of the frequency of these epeirogenic oscillations depends upon a consideration of the conditions under which the marl partings were deposited. In this case there is no direct help forthcoming from the Bahaman area since terrigenous sediment is almost absent even to great depths. The following considerations suggest that the marl was deposited in deeper water than the limestone.

Greater precipitation of $CaCO_3$ in shallower water is to be expected on chemical grounds (higher temperature aided by higher salinity due to surface evaporation). This can apparently be demonstrated in the Bahamas (Newell, 1955). Assuming then a uniform but small supply of terrigenous material, epeirogenic oscillations would, under certain conditions, allow the formation of slightly impure limestones in shallow water and marl in deeper water.

A prediction is possible. Let us assume that, in a given stretch of sea, lime mud is deposited from sea-level down to a depth of x feet and marl from x feet downwards. The sea-floor in one area, case (a), oscillates about a mean within the zone of 'limestone' deposition and in a neighbouring area, case (b), about a mean at x, i.e. at a given time the sea-floor is deeper in the latter area. In case (a) the sea-floor periodically emerges above sea-level to form land and then sinks to just within the marl zone. In case (b) there is no emergence and proportionately more marl will be deposited as more time is spent in the marl zone (Fig. 3). Therefore in an area where the White Lias has a higher marl/limestone ratio there should tend to be an absence of phenomena indicative of emergence. Just such a condition is realised at Tolcis in the top six feet of the White Lias (Hallam, 1957). There is no trace in the limestones of any of the features mentioned at the beginning of this section.

According to this interpretation, then, each limestone-marl rhythm or cyclothem represents an epeirogenic oscillation. Sixty is a conservative estimate of the number of minor cyclothems in the Pinhay Bay section. An accurate estimate is impossible because of lateral passage and wedging out.

Thick limestones are probably equivalent to several cyclothems. Minor slumping phenomena tend to destroy evidence by breaking-up marl partings. The sharp distinction between limestone and marl, the latter filling out irregularities in the limestone surfaces, calls for comment. It is tempting to speculate, in explanation, that the limestones were deposited on a shallow platform which fell away sharply to much deeper water, like the present Bahama Banks. The sharp succession of marl upon consolidated limestone indicates that subsidence must have been too rapid to allow time for a significant deposition of lime mud in this part of the cycle. The rhythm seems therefore to have been asymmetric (Fig. 3).

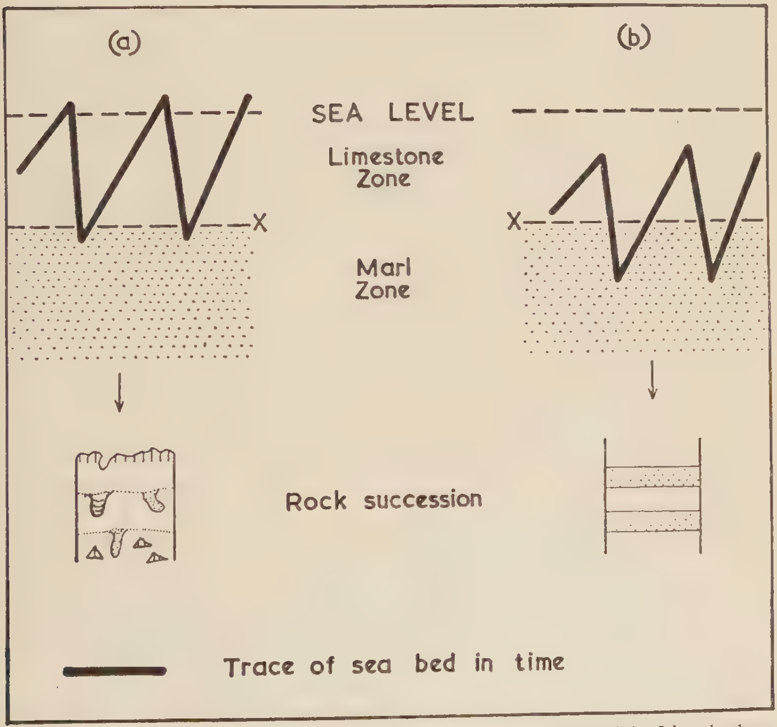


Fig. 3. Diagram to illustrate the epeirogenic theory of origin of the White Lias rhythm; explanation in text

Despite the oscillations, which might have had amplitudes of only a few fathoms, the configuration of land and sea must have remained broadly similar for long periods. In this connection it is interesting to note the evidence in the Bahaman area for a number of recent oscillatory movements of sea-level, which has always returned to about the same position (Field *et al.*, 1931, 782).

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REFERENCES

ARKELL, W. J. 1933. *The Jurassic System in Great Britain.* Oxford.

BLACK, M. 1930. Great Bahama Bank—a Modern Shelf Lagoon. *Bull. geol. Soc. Amer.*, **41**, 109.

————. 1933. The Precipitation of Calcium Carbonate on the Great Bahama Bank. *Geol. Mag.*, **70**, 455.

DUNNINGTON, H. V. 1945. Contemporaneous Slumping in the Embsay Limestone Series of the Skipton Anticline. *Proc. Yorks. geol. (polyt.) Soc.*, **25**, 239.

FIELD, R. M. *et al.* 1931. Geology of the Bahamas. *Bull. geol. Soc. Amer.*, **42**, 759.

HALLAM, A. 1957. The Rhaetic and Liassic beds of Tolcis, near Axminster. *Proc. Dorset nat. Hist. Fld Cl.*, **78**, 63.

ILLING, L. V. 1954. Bahaman Calcareous Sands. *Bull. Amer. Ass. Petrol. Geol.*, **38**, 1.

JONES, O. T. 1937. On the Sliding or Slumping of Submarine Sediments in Denbighshire, North Wales, during the Ludlow Period. *Quart. J. geol. Soc. Lond.*, **93**, 241.

KUENEN, P. H. 1948. Slumping in the Carboniferous Rocks of Pembrokeshire. *Quart. J. geol. Soc. Lond.*, **104**, 365.

KULP, J., K. TUREKIAN & D. W. BOYD. 1952. Strontium Content of Limestones and Fossils. *Bull. geol. Soc. Amer.*, **63**, 701.

LANG, W. D. 1924. The Blue Lias of the Devon and Dorset coasts. *Proc. Geol. Ass., Lond.*, **35**, 169.

LOWENSTAM, H. A. & S. EPSTEIN. 1957. On the Origin of Sedimentary Aragonite Needles of the Great Bahama Bank. *J. Geol.*, **65**, 364.

NEWELL, N. D. 1955. Bahaman Platforms. *Geol. Soc. Amer. Spec. paper*, **62**, 303.

———— *et al.* 1953. *The Permian Reef Complex of the Guadaloupe Mountains Region, Texas and New Mexico.* San Francisco.

REVELLE, R. & R. FAIRBRIDGE. 1957. Carbonates and Carbon Dioxide. *Geol. soc. Amer. Mem.* 67, **1**, 239.

RICHARDSON, L. 1906. On the Rhaetic and Contiguous Deposits of Devon and Dorset. *Proc. Geol. Ass., Lond.*, **19**, 401.

RICHTER, R. 1926. Flachseebeobachtungen zur paläontologie und geologie XII. Bau, begriff und paläogeographische bedeutung von *Corophioides luniformis* (Blanckkom, 1917). *Senckenbergiana*, **8**, 200.

SMITH, C. L. 1940. The Great Bahama Bank. II. Calcium Carbonate Precipitation. *J. Mar. Res.*, **3**, 171–89.

STOCKDALE, P. B. 1926. The Stratigraphic Significance of Solution in Rocks. *J. Geol.*, **34**, 399.

Summer Field Meeting in East Anglia

14–24 August 1958

Report by the Directors: D. F. W. BADEN-POWELL and R. G. WEST

Received 26 March 1959

THE OBJECT of the Field Meeting, centred on Ipswich and Norwich, was to study the Pliocene and Pleistocene rocks of the area, with special reference to the fossil plants and animals and the modern techniques which have been devised for investigating them. Naturally the glacial deposits, geomorphology and coastal processes of the district attracted attention, and these have also been the subject of new and recent research. About twenty-five members and friends attended the meeting, and others were welcomed for occasional days, including Mr. Rainbird Clarke, curator of the Norwich Castle Museum, and Mr. A. T. Marston. Valuable assistance was given by Mr. H. E. P. Spencer of the Municipal Museum at Ipswich, and his expert knowledge of the details of the sections around Ipswich contributed much to the enjoyment and success of the meeting.

Use was made at some sites of unpublished work by Mr. Rainbird Clarke, Mr. P. Cambridge and Miss Ann Stevens. The Directors are most grateful to these experts and to Professor S. W. Wooldridge for their important contributions to the success of the meeting; to Dr. G. Larwood for identifying Polyzoa; to Mr. M. P. Kerney and Mr. B. M. Funnell for help in many ways, and to Miss Barbara Green for her efficient work as the meeting secretary.

The party assembled in Clare College, Cambridge, on the evening of Thursday, 14 August, and the Directors and members attending the meeting are extremely grateful to the Master and Fellows of the College for permission to spend the first night of the meeting in the College and in one of the College lodgings. Before dinner in Hall, a brief account was given by Mr. Baden-Powell of the recent research which has been undertaken in East Anglia and of some of the sections to be visited during the excursion. After dinner a visit was paid to the University Sub-Department of Quaternary Research, where a most interesting account of the work of this organisation was given by the Director, Dr. H. Godwin, and a spectacular series of exhibits had been arranged showing the methods and results of pollen-analysis as used both for Holocene and Interglacial beds, and included other work on glacial geology and vertebrate palaeontology.

Copies of a list showing the Pliocene–Pleistocene–Holocene succession in East Anglia were handed out to members of the party; the following is an abridged version of this list:

Strata	*Implements*
Holocene fen deposits	Mesolithic to Romano–British
Hunstanton Brown Till	? Upper Palaeolithic
March Gravel and Morston Raised Beach	Levalloisian
Gipping Till and gravel	Levalloisian
Hoxne Interglacial	Acheulian and Clactonian
Lowestoft Till	Derived flake implements
Corton Beds	Flake implements
North Sea Drift with Cromer Till and Norwich Brickearth	Derived Abbevillian
Leda myalis Bed	
Cromer Forest Bed	
Weybourne Crag	Early flake industry
Chillesford Clay	
Norwich Crag	Abbevillian
Red Crag	Abbevillian and earlier implements
Coralline Crag	

A similar table of strata was also produced by Mr. Spencer which referred mainly to Suffolk.

The party had exceedingly good luck with the weather, and no loss of geological work was caused by rain during the ten days of the meeting.

Much regret was felt that Professor P. G. H. Boswell was not able to lead this excursion; his extensive work on this area (see Boswell, 1931, 1933, 1937, and 1952, and numerous earlier papers) was recognised as the basis of much work that has been done recently.

Friday, 15 August

The party travelled by coach from Cambridge to Ipswich, and stopped *en route* at a few places. Stone stripes were examined at Risby Poor's Heath, south-east of Cavenham (52/777678) and at Thetford Heath, east of Elveden (52/847796). At the former site a small chalk pit showed the stone stripes in section, with involutions between light brown sandy marl and sludged chalk rich in flints. It was generally agreed that the stripes and the involutions were the result of periglacial climatic conditions, but the explanations of the details of structure seen in the sections proved difficult.

At Thetford Heath, the stone stripes described by Dr. Watt (1955, 173) were examined. They were seen to consist of ridges of hard chalky flinty material, alternating with furrows and often more sandy soil. It was noted that the striping affected the nearby vegetation, grassland occurring on the ridges, but heather (*Calluna vulgaris*) growing on the deeper sandier soils between the ridges. Dr. West pointed out that the vegetational patterns resulting from the soil differences made the periglacial features easy to distinguish in aerial photographs.

The next pause was at Lopham Ford, the common source of the Little

Ouse and the Waveney (62/039730). This was described as the lowest col in the Chalk Escarpment between Hunstanton and Goring Gap, height of the ground surface here being about eighty-six feet O.D. Former theories of glacial erosion and reversed drainage were mentioned to account for this low gap, but it has been suggested by Mr. Baden-Powell (1944, 211–12) that another possible explanation was that this is a glacial overflow channel from 'Lake Ouse', the supposed most southerly part of the Yorkshire glacial lakes made famous by Professor Kendall. Professor Wooldridge accepted this explanation and commented that this was not the first time he had heard it put forward.

After lunch at Hoxne, the brickyard there was visited (62/175766). Dr. West gave a short outline of the history of investigations at Hoxne. The site was famous because John Frere at the end of the eighteenth century was the first to recognise the antiquity of the hand-axes found during the working of the pits here. Since that time, the deposits had been investigated by Clement Reid and Reid Moir. Their results, together with those of recent work (1956, 265), showed that at Hoxne a lake existed in a hollow in the surface of the Lowestoft Till during interglacial times. In the lake were deposited a series of clays and organic muds, which were subsequently sealed in by periglacial and glacial deposits related to the Gipping Glaciation. A pollen diagram from analyses of the lake deposits was shown and the succession of vegetation described. An early bleak phase with birch scrub was followed by the development of mixed oak forest, which persisted for a great part of the lake history. The mixed oak forest was replaced by coniferous forest with spruce (*Picea*), silver fir (*Abies*) and pine (*Pinus*). The final phase was shown in the uppermost lake deposits, a brecciated clay-mud, which contained remains of such cold-loving plants as the dwarf birch (*Betula nana*) and arctic willows. The vegetational succession gave good grounds for correlating the Hoxne Interglacial with the Elster/Saale Interglacial of the continent. Palaeolithic artefacts of late middle Acheulian type had been found in the lake deposits, and it was possible to relate this industry to the vegetational succession; it occurred towards the middle of the interglacial.

The party examined sections on the west side of the Hoxne–Eye road, where they saw the underlying Lowestoft Till in the north-west corner of the pit, the lake deposits, including the brecciated clay-mud, in the centre of the west face, and the covering deposits at the south end of the pit. Dr. West pointed out that the covering deposits were extremely variable, being evidently solifluxion deposits in some places, and till, aeolian and stratified water-lain beds in others. It was possible that some of these covering strata were part of an old river system related to the Little Ouse–Waveney Valley. Finally it was noted how much the topography had changed since the time of the interglacial lake. Now the lake deposits were on a ridge between two valleys, tributary to the River Waveney. The present features of the topography thus originated later than the Hoxne Interglacial.

On arrival at Ipswich, the party gratefully accepted the invitation to tea by the authorities of the Municipal Museum, and Mr. Spencer demonstrated the magnificent collection of Crag and other fossils, including the unique mammalian fauna from the Suffolk Bone Beds below the Crags. The important collection of palaeoliths and other implements was also a centre of attraction.

Saturday, 16 August

On the way from Ipswich to Orford, the approximate position of the Foxhall section in the Red Crag was indicated to the party in the coach, and mention was made of the 'Foxhall Jaw', a phosphatised jaw of hominid type which was found about 100 years ago, allegedly in the Red Crag, but is not at present available for further investigation, as it was taken to the United States where it was lost. A flat feature of the landscape near Martlesham Heath, near Woodbridge, was pointed out as due to sandy outwash material, probably from a Gipping ice-front. The site of the famous Sutton Hoo Ship Burial (Saxon) was also pointed out near Melton

The party then visited a section in the Coralline Crag, on the principle of working upward through the succession as far as the topographical distribution of the rocks would allow. The site chosen was a comparatively little-known one on the left bank of the Butley River, just above high-water mark, at a point called The Cliff (62/397486), west of Orford. Although most maps only mark a footpath to this point, a track to a cottage was found down which the bus could go most of the way to the shore. Mr. Baden-Powell explained that this is the only open fossiliferous section at present available for the lower shelly sand in the Coralline Crag, apart from Sutton, near the River Deben, although the higher Bryozoa rock is accessible at Aldeburgh and other places. A short history was given of the attempts by Prestwich, A. Bell (1911, 296) and Harmer to subdivide the Coralline Crag into zones, but it was suggested that the Crag across the Butley River at Boyton did not necessarily belong to the Coralline Crag, as suggested by Bell, and therefore on the present evidence it is not advisable to use the Zonal names 'Gedgravian' and 'Boytonian'. The warm climate represented by the Coralline Crag was confirmed in the field by the presence of the small lamellibranchs which now live in the Mediterranean, *Cardita corbis*, *Woodia digitaria* and *Cytherea rudis*, and among other fossils the extinct form *Terebratula grandis* was found to be fairly common.

After the section in the Bryozoa rock (upper part of the Coralline Crag), in a pit across the road from Richmond Farm, Orford, had been much photographed, owing to the distinctive cross-bedding which shows up on its weathered surface, a visit was paid to Orford Castle. Its building stones came in for comment, consisting of London Clay septaria in vast numbers, what appeared to be Barnack Stone, and pink cement blocks. The site of the castle was used as a vantage point from which to view the great shingle bank of Orford Ness, and to observe the way the shingle diverts the Rivers Alde and Butley southward along the coast for many miles before they can reach the sea. A reference was made to Professor Steers's work on the rate of growth of the spit (1926, 306), and it was explained that if this Norman castle (built by the year 1166) was placed here in order to guard the mouth of the river, that means that about half the spit as we see it had been formed by 1166. It was emphasised that the rate of growth is known to have been irregular, but that if Clement Reid was right in thinking there has been no change of sea-level since about 1500 B.C., the spit has had ample time to grow. On the other hand, the more recent work by Longfield (1933, 73) and by Charles Green suggests that there have been considerable changes of level on this part of the coast since 1500 B.C., and the party was told that work is now being done to try to find out how much vertical movement has taken place and to what extent this has affected the coastal evolution. Reference was also made to the fact that most of the shingle consists of flint, but that some pebbles of igneous and metamorphic rocks are also found; investigation of the origin of the shingle is only just beginning, but a preliminary opinion suggests that some of the shingle is derived from the North Sea Drift, many miles farther north. During this discussion, some of the party visited the nearby crag pit, which is very overgrown, and saw some Coralline Crag sand with Bryozoa.

After lunch at the Butley Oyster Inn, well known to generations of geologists, a visit was paid to the Neutral Farm pit in the Red Crag (Butley 'Zone') (62/371510), where an excellent section was found. A general description of the Crag 'Zones' was given, based on F. W. Harmer's work (1900, 751), and the point was emphasised that it was very difficult to rely on any accuracy based on percentages of extinct shells or other similar calculations, owing to the personal element in the geologists who carried out the identifications. *Neptunea contraria* had already been described as a zonal fossil in the sense that it is unknown from the Coralline Crag and is therefore typical of the Red Crag series. Within narrower bounds, the shell *Cardium angustatum* was then described as being known mainly from the Newbourne and Butley sub-divisions of the Red Crag, and this shell was duly found in the Neutral Farm pit, together with many others including *Tellina obliqua*, *Mactra ovalis*, *Saxicava* cf. *arctica*, *Calyptraea chinensis* and *Sipho propinquus*. Mr. Cambridge pointed out that he had identified some non-marine shells from a particular layer in this section.

The next sections seen were at Chillesford, first the 'Church' pit (62/383523) then the 'Stackyard' pit (62/385522). Freshly cut sections showed the usual banded silt in the 'Church' pit with *Mya* shells in position of growth, and a cut down to about eight feet deeper exposed grey silty sand with many shells including *Scrobicularia plana*, the zonal shell here which caused Searles Wood to name this deposit the *Scrobicularia Crag*. This same fauna appears at the top of the section in the next 'Stackyard' pit, at a slightly lower level, and the crag here is also of the same grey colour. Mr. Cambridge excavated a foot or two down in the floor of the pit to show that typical Red Crag here underlies the grey *Scrobicularia* Crag. He proposed that the grey crag with *Scrobicularia* should be considered as the basal bed of the Norwich Crag series in this area. Some of the party visited Chillesford church, which had been pointed out as one of the few churches here built partly of Coralline Crag.

Sunday, 17 August

Mr. Spencer conducted the party to the large chalk pit at Bramford. three miles north-west of Ipswich (62/128482), as a general introduction to the stratigraphy of the Ipswich district. This huge pit is no longer working. and the succession was pointed out from a distance, as the sections are not as good as they were. The chalk was described as being followed upwards by the Thanet Beds and Reading Sand, London Clay (mainly developed in the adjoining brickfield) and decalcified Red Crag. Mr. Spencer said the Crag here is overlaid by gravel which Dr. Solomon had correlated with the Westleton Beds, and the whole is capped in places by a little Gipping Till. Mr. Baden-Powell added an observation that he had collected some of the erratics from the supposed Westleton Beds here, and they were of Thames type, including the porphyritic rhyolite. He also said that Mr. Reid Moir had collected some of his Pre-Crag implements from the base of the Crag in this pit, and had named them Bramfordian after this locality.

The next pit visited was the famous Claydon Cement Works, west of Claydon station and south of Great Blakenham church (62/117498). Mr. Baden-Powell pointed out that this is the type-section after which the Gipping Till was named (Baden-Powell, 1948, 285), and that this glacial bed can be seen overlying the earlier Lowestoft Till on the north side of the entrance to the pit. Dr. West took a party to see the place where the stone orientations had been measured in the two tills (West & Donner, 1956, 83), giving results which agreed here with the directions of ice-movement determined from the matrix and erratics of the two beds; Mr. Spencer also showed members an example of banded clays between the two tills at the western end of this huge quarry.

After lunch Mr. Spencer took the party to a gravel pit one mile west-north-west of Barham church (62/122510), and explained that this deposit forms slight knolls in the flood-plain of the River Gipping, and that as remains of mammoth and reindeer have been found, he considers this bed to be of glacial origin, and there is no indication that it coincided with any interglacial episode. The party found an interesting mixture of erratics, including Cheviot Porphyrite which could have been derived from the Gipping Till mixed with Greensand Chert of Thames type, which could presumably come from the Westleton gravel as seen under the Gipping Till at Bramford. Other erratics included Bunter pebbles and a dark red sandstone of possible Upper Carboniferous or Old Red Sandstone origin.

Then the extensive gravel pits were visited near Creeting St. Mary, above the left bank of the Gipping, north of Needham Market (62/095555). Mr. Spencer explained that at the base of the sequence here there is an important sand formation which might be decalcified crag or a later glacial sand or possibly Corton Beds. No definite fossils have been found in this bed, and it is overlain in one place by a little clay and a thin bed of till, which may belong to the Lowestoft glaciation. These deposits are succeeded upwards by a great thickness of gravel overlain by a till, both of which are correlated with the Gipping glaciation. Fragments of marine shells occur in the Gipping Gravel, and those found during this visit have been identified by Mr. Cambridge as: valves of *Balanus* sp., *Mytilus*, *Cardium*, *Chlamys*, and a tooth of *Chrysophrys* sp. with a note that the fragments found are too minute to allow more accurate determinations.

Mr. Baden-Powell said that the erratics are much the same in the Gipping Gravel and the Gipping Till here, and include a mixture of rocks of northern derivation such as Cheviot Porphyrite, gannister (or Jurassic carbonaceous sandstone), ? Whin Sill, and Millstone Grit with rocks of Thames Valley type including porphyritic rhyolite, ? sarsen, dark coloured Bunter pebbles, Hertfordshire Puddingstone, silicified oolite and a tourmaline breccia which was also considered to have come through the Bunter.

Finally, after tea in Needham Market, this tour of the geology of the Gipping Valley was brought to a climax by a visit to the recently discovered beach deposits of the Crag sea, a short account of which has been published by Mr. Spencer (1951, xxvi). The section south-east of Battisford (62/063540) showed well-rounded flint shingle with very few other rock fragments of any kind, except for small phosphatic pebbles. As far as is known, this is the first time a shore deposit of the Crag sea has been seen in this area, and its height has been determined as about 150 feet O.D. Mr. Cambridge said that as the lamellibranch *Cardium angustatum* has been found among other shells in the lower part of the deposit, it is unlikely to belong to an earlier stage of the Red Crag than the Newbournian. No mollusca were seen during this particular visit except one cast of *Mactra* sp., but derived teeth found by Mrs. E. M. Evans have been identified by Mr. Cambridge as belonging to the genera *Myliobatis*, *Aetobatis* and *Lamna*. Mr. Larwood has reported that members of the party also collected several specimens of Cheilostome Polyzoa preserved in hollows in battered flint pebbles. These included *Escharella immersa*, three specimens; *Amphiblestrum trifolium*, eight specimens; and *Electra* sp., two specimens. One worn zoarial fragment may be assigned to *Microporella* sp. Mr. Spencer said that pebble tools had been found here similar to those from Darmsden.

Monday, 18 August

This day was occupied by travelling from Ipswich to Norwich, and important sites at Aldeburgh, Westleton and Corton were visited on the way. At a point near Wickham Market, north-east of Woodbridge, the flat nature of the country was pointed out as due to the Gipping Till here acting as a cap-rock which prevents the erosion of the relatively soft sands underneath it; the contrast was mentioned between this feature and the flat country which had been seen two days previously which was due to a flat expanse of outwash sands.

The first section seen was in the Aldeburgh brickworks, south-west of the railway station and south of the road to Snape (62/452572). The sequence here showed:

3. Chillesford Clay
2. ? Norwich Crag
1. Coralline Crag.

Mr. Spencer described the section and emphasised that there is a tendency for the shells made of calcite to be preserved in the Coralline Crag here, while those made of aragonite are dissolved away. The fossils found in the pit included one identified by Mr. Spencer as a vertebra of the dolphin *Tursiops tursio*. The crag which overlies the Coralline here is the same greyish colour as that classed as Norwich Crag in the Chillesford Stackyard Pit, and mollusca found at Aldeburgh included the Zonal shell *Scrobicularia plana* and also *Cardium angustatum*, which showed that the Red Crag zonal shells had not all died out at this early stage in the later Crag. No fauna was found in the Chillesford Clay in this pit.

The section seen in the Westleton Beds was in the large pit in the southern part of Westleton village (62/443685); this pit has shown very extensive exposures until recently, but is now partly filled in. The well-bedded shingly sand was best seen just below the windmill near the lane to Scott's Hall. Mr. Baden-Powell said that water used to be held up in the lower parts of the pit by an underlying clay which looked like Chillesford Clay, although no fossils had been found in it. He also said that sections at Somerleyton brickworks, south-west of Yarmouth, used to show shingly sand underlying North Sea Drift. The opinion was expressed that if these two sections had been rightly interpreted, the age of the Westleton Beds should come somewhere between the Chillesford Clay and the North Sea

Drift. Mention was made of some shells collected by Prestwich near Southwold (see *Southwold Memoir*, 1887, 82–4) which are similar to a normal fauna from the upper part of the Norwich Crag, but did not include *Tellina balthica*, which would indicate correlation with the Bure Valley Beds. The south-easterly dip seen in this section was described as constant over a wide area between Harleston and the coast at Dunwich, and whatever the exact age of the deposits, they seem to be of marine origin. A short account was given of the erratics collected many years ago by Salter, who showed that they were derived from the Thames Basin, although Solomon had later revived the old theory that some of the pebbles could come from the Ardennes. No marine fossils were found during this visit, but several erratic pebbles, including chert from the Greensand, were found by the party.

During a discussion in this pit, Professor Wooldridge considered that the Westleton Beds were to be correlated with the pebble gravels at 400 feet in the Thames Basin. Mr. Spencer said that a whale vertebra had been found not long ago in the Westleton Beds, but was much too fragile for exact identification: he also said that an example of the shell *Purpura lapillus* was said to have been found in the large pit in these beds at Holton, near Halesworth.

The coast section was then visited at the north end of Corton village (62/544977), between Lowestoft and Yarmouth, but the modern beach was found to be so high that it concealed the Forest Bed at the base of the cliff, and unfortunately recent cliff falls had obscured much of the section. However, it was possible for the party to see the brown 'stony loam' of the North Sea Drift just above modern beach level, and the contrast between this and the black Lowestoft Till with pebbles of hard chalk at the top of the cliff was very striking. Between these two, the sands of the Corton Beds could be seen in places, but unfortunately the marine shell-beds were not seen here because of the cliff-falls. Mr. Baden-Powell reminded the party that the shells in this bed were considered to be derived Crag shells until about 1870, when Searles Wood showed that most of the strong Crag shells which should be expected in these sands are completely absent, and that part of the fauna has never yet been found in any part of the Crag series. Wood and Harmer were convinced that at least part of the marine fauna at Corton is indigenous and not derived (Baden-Powell, 1950, 195–7).

The party then proceeded to Norwich, headquarters for the remaining days of the meeting.

Tuesday, 19 August

The morning was spent in Norwich, and the party was welcomed at the Castle Museum by the Curator, Mr. R. R. Clarke, who explained the history of this wonderful museum. Here, much time was spent in studying the shell collections, the vertebrate remains from the Cromer Forest Bed, the room devoted to the geology and coastal processes of Norfolk. A second gallery devoted to Prehistory, the 'Norfolk Room' with its grand series of natural history dioramas, and many other objects of interest were also examined.

After lunch at Whitlingham a series of sections near Norwich was visited. The first of these was the famous chalk pit near the river on the Crown Point estate (63/267076), where the base of the Norwich Crag was examined resting on the Chalk; the section was found to be rather limited, as the pit was very badly overgrown. Mr. Baden-Powell explained that this bed belongs to the upper part of the Norwich Crag which is usually characterised by the first arrival in quantity of the Scandinavian shell *Astarte borealis*, although this shell was not found in this pit during this particular visit. A small part of a deer antler was excavated from the Stone Bed at the base of the Crag, and marine shells included *Chlamys opercularis*, *Mya arenaria* (two individuals in place of growth), the Mediterranean shell *Turritella incrassata* and another warm indicator *Loripes divaricatus*.

The original idea had been to examine the famous Crag pits at Thorpe, east of Norwich, but these now show no Crag, and instead the type area of F. W. Harmer's 'Fluvio-marine Crag' was visited at Bramerton (63/297060), and here the pits have so degenerated that some of the party had to clear a section with spades. They were rewarded by finding Harmer's fauna, which included some of the distorted examples of *Littorina littorea* and other gasteropods, whose shapes were explained by Harmer as due to abnormal salinity conditions near the mouth of a river. A rich fauna was found here including *Cardium edule*, *Tellina obliqua*, *Tellina praetenuis*, *Mactra ovalis*, *Tapes rhomboides*, ? the extinct *Rissoa minuta*, also *Cerithium tricinctum*, *Scalaria* ? *similis*, various forms of *Purpura lapillus*, including var. *newbourniensis* which had been found here by Harmer, and *Buccinum undatum* var. *striata*. The assemblage of shells was pointed out as typical of this part of the Norwich Crag at an horizon not quite young enough to include *Tellina balthica*. Mr. Cambridge took away material for washing and sorting, and has identified the following in addition to the above list: *Purpura lapillus* var. *ventricosa* and var. *elongata*, *Littorina saxatilis*, *Potamides icenicus*, *Scalaria groenlandica*, *Melampus pyramidalis*, *Bela pyramidalis*, *Ringicula ventricosa*, *Hydrobia ulvae* (very common), a form of *Neptunea despecta*, a *Turritella* attributed to *communis*, *Calyptraea chinensis*, *Cyprina islandica*, *Mya arenaria*, various varieties of *Cardium edule* (very common), *Yoldia myalis*, *Mytilus edulis* (very common), *Spisula truncata* (very common), *Corbula* ? *contracta*, *Saxicava arctica*, *Venus fasciata*, *Hemithyris psittacea* and various crab and fish remains. In addition a fragment was found of a Jurassic ammonite, identified by Dr. Callomon as *Pavlovia* cf. *rotunda* from the Kimmeridge Clay. The Crag fauna has been quoted at length here partly because little has been published recently on the fauna of the Norwich Crag, and partly to show how richly fossiliferous a chance section can be. Mr. Baden-Powell considered that the climate represented was rather cold, but with some warm indicators.

At the next section, in the Catton brickworks north of Norwich (63/234130), a little of the Bure Valley Bed gravel was seen with its typical small vein quartz pebbles underlying slightly laminated Norwich Brickearth with a few stones. Dr. West said that the stones in the brickearth gave an orientation which suggested ice-movement from the north-west. It was usually considered that the Norwich Brickearth, in most places decalcified as it is at Catton, belonged to the same major glacial episode as the Cromer Till, both forming the North Sea Drift. Certainly both were known to give a similar direction of orientation of their contained pebbles. Decalcification was not necessarily a bar to their inclusion in the same glacial episode, as sections of the Norwich Brickearth were known where covering deposits preserved its calcareous content. But more investigation of the complex of tills included within the term Cromer Till was needed before their inclusion in the same glacial episode could be made certain.

Professor Wooldridge put forward a correlation of the Bure Valley Bed, seen underlying the Norwich Brickearth, with the Westleton Beds and the 400 foot pebble gravels of the Thames Basin. Mr. Baden-Powell added the information that as well as various northern rocks, the erratic pebbles from the Norwich Brickearth had been described by Dr. Kenneth Harrison as including some Lake District specimens. Some members of the party tested the Norwich Brickearth here with acid and found it apparently decalcified throughout its thickness, and Mr. Cambridge found some impressions of shells which showed that mollusca had originally been included in the deposit.

In the meantime Mr. R. R. Clarke had rejoined the party and acted as guide to a gravel pit being worked at Keswick, south of Norwich (63/213051). This pit is at a height of forty-two feet O.D. and the deposit forms part of the infilling of the valley of the River Yare. This site has become well known since November 1956 for the large number of palaeoliths found (Acheulian and Clactonian), about fifty 'hand-axes', eight cleavers, 100 flakes and other types having been taken to the Norwich Museum from here. Most members of the party found one or two humanly flaked objects, and the driver of the mechanical digger laid out eleven 'hand-axes' on the floor of his cab for our inspection; these are included in the above totals and are now in the Museum. The erratics in this gravel included a crinoidal chert, presumably from the Pennine or Welsh Carboniferous. There seems to be no record of any fossil plants from this pit yet, but one ox tooth and fused vertebrae (? horse) from this pit may be as old as the implements.

Wednesday, 20 August

On the way from Norwich to the coast, a short stop was made at Filby Broad (63/462135), where Dr. West spoke of the most interesting work done recently by Dr. Lambert, Mr. Clifford Smith and Mr. Charles Green on the origin of the Broads. The Post-Glacial infilling of the Broadland valleys with peats and estuarine clays was described, and the stratigraphical and historical evidence for flooded medieval diggings in the peat was recounted. Close borings in the peat had shown abrupt changes in the stratigraphy which could only be explained by the presence of artificial excavation, and medieval records had given evidence of extensive peat production in the areas now forming the Broads.

The first point visited on the coast today was north of Yarmouth at Scratby. The party walked north along the coast from a point south of California Gap (63/549126) to Scratby Stairs (63/514154), and the first section seen was in the cliff south of California Gap. Here a bed of shelly sand was seen resting on shelly North Sea Drift, with apparently another bed of North Sea Drift on top of both these deposits. Mr. Baden-Powell explained that during an earlier visit by the Association the shelly sand was thought to be Corton Beds (Baden-Powell, 1950, 193) and this age was also given to this sand in a paper by C. Green, G. P. Larwood & A. J. Martin (1953, 336), although they considered that part of the fauna was derived from some earlier bed. The suggestion was now made that as the new sections seemed to show that the shell-bed is in rather than above the North Sea Drift, and as the fauna (now being studied) is not quite typical of the Corton fauna, this shell-bed may be an erratic of some earlier deposit which was carried by the ice in a frozen state. Mr. Cambridge has identified some of the shells from the shelly sand as: *Cardium edule*, *Turritella incrassata*, *Astarte montagui*, *Pectunculus glycimeris* and fragments of other species; he noted that *Balanus* plates were very common. To the north of California Gap typical dark-coloured Lowestoft Till was seen above the North Sea Drift at the top of the cliff.

The party then drove along the coast road to the site of the lost village of Eccles, where the ruins of the church tower were seen between tide-marks on the beach (63/414288). An earlier statement had been made by Mr. Baden-Powell that the arrangement of sand and shingle along this coast tends to be partly symmetrical about a north-east to south-west axis: that is to say, most of the shingle seems to get swept westward towards Blakeney Point and southward towards Orford Ness, and the beach is most sandy at this intermediate point near Eccles. This preponderance of sand here may account for the concentration of dunes at this part of the coast, and these dunes are able to accumulate and to move slowly inland owing to the lack of cliffs just here. The rate of movement of the dunes can be studied from the unfortunate history of the village of Eccles: three rough sketches were shown to the party, two reproduced from the works of Lyell, showing the church tower on the landward side of the dunes in 1823, in the middle of the dunes in 1839 and on their seaward side by 1862. The tower finally fell during a great storm in 1895 and today the ruins were seen about half-way down the beach.

After lunch at Happisburgh, the party went down to the beach at a point east-south-east of the village (63/393305) and saw a section in which the North Sea Drift deposits are tilted at a gentle angle and consist of alternate till and laminated beds. The suggestion was made that one possible explanation of these alternations is that there was a fluctuating ice-front resting in a system of glacier lakes. The party was reminded that nearly a hundred years ago Thomas Belt had published a theory that ice resting on what is now the bed of the North Sea would dam up the rivers flowing from eastern England and the Rhine basin, and that the overflow from the resulting lakes might have eroded a valley southwards which eventually became the Straits of Dover. A statement was also made that Searles Wood considered that a stony brickearth which caps all the cliff sections along here might be the Hunstanton Till. Mr. Baden-Powell thought there was some evidence to support this idea, but Dr. West disagreed. In the meantime Mr. Cambridge collected many shell fragments from the blue till at the base of the section, which he has identified as: *Cardium edule* (common), *Tellina balthica* (common, some valves almost complete), ? *Cyprina islandica*, *Acila* sp., *Mya* sp., and *Ostrea* sp. Most of the shells were fragmentary.

While passing Walcot Gap (63/360330), some sand dunes were pointed out which are invading the gardens of the houses along the top of the new sea-wall, and it was explained that these have grown since the great storm of 1953, and that before that date there had been a meadow and small cliff between these houses and the sea. Amongst the famous erratics around the King's Arms Hotel at Bacton, one of laurvikite and another of columnar basalt were seen.

Thursday, 21 August

After Mr. A. T. Marston had joined the party, the coast section south-east of the end of the promenade at Overstrand (63/252410) was visited at the suggestion of Mr. M. P. Kerney, in order to see the Weybourne Crag exposed not long ago by the removal of a talus slope by the sea. This crag, consisting of shelly sand with grey silty layers, was found about twelve feet thick on the top of a mass of displaced chalk. The point was emphasised that the party had at last ascended high enough in the sequence to see a crag which contains *Tellina balthica* as one of its most abundant shells. At the same time it was pointed out that this shell by no means represents specially cold conditions, as has been believed by some geologists. In addition to this mollusc, others found included three extinct species, *Nucula cobboldiae*, *Leda oblongoides* and *Tellina obliqua*, as well as the common intertidal forms *Cardium edule* and *Littorina littorea*, which point to shallow-water conditions. Mr. Cambridge has also identified microtine and fish teeth and the marine mollusca *Leda myalis*, *Lucina borealis*, *Mactra ovalis*, *Mytilus edulis*, *Scalaria groenlandica* and *Cyprina islandica*.

After lunch at East Runton, the party walked along the shore from East Runton Gap (63/200428) to West Runton Gap (63/185433). Immediately on the west side of East Runton Gap, a large amount of heavy gravel was seen contorted into the top of the cliff, and this was interpreted as probably belonging to the glacial gravel to be seen at Briton's Lane pit the following day. Near it was also a contorted mass of Corton Beds, in which Mr. Larwood found a *Natica* sp. As the party followed the coast section westward, the huge glacial contortions were seen in places to cut right down to modern beach level, but in others they seemed to affect the upper part of the cliff more than the lower. Here and there the lower part could be recognised as only partially disturbed North Sea Drift, and much of the volume of these masses was taken up by the huge chalk erratics, some of which could be seen to be in an almost horizontal position judging by the lines of chalk flints, although other chalk slabs were bent and even broken. An account was given of the part these enormous chalk erratics had played in the old controversies of floating- versus land-ice, and by the latter theory it was shown that the chalk erratics are most easily explained as parts of the surface of the Chalk sheared off, which need not have been moved more than a few hundred yards.

Just before reaching West Runton Gap from the east, a large contorted mass of Corton Beds was examined near the top of the cliff. This was more than usually shelly, and although its fauna was mostly marine, it also included some non-marine material, such as a *Paludina* sp. and one *Valvata goldfussiana*, the latter identified by Mr. Kerney who considers it to be a Cromerian form. Mr. Cambridge has identified the following marine mollusca from this patch as including the extinct *Nassa reticosa* var. *costata* (one), *Cardium edule* (common), *Tellina balthica* (some fairly complete), *Mya* sp., *Cyprina islandica* and a *Littorina* sp., with the comment that the non-marine material is better preserved than the marine shells.

Another centre of attraction immediately east of West Runton Gap was an exposure of the top of the Cromer Forest Bed, showing just above modern beach level. This consisted of black peaty clay which contained *Unio*, *Anodonta*, *Paludina*, a *Cervid* tooth, remains of an *Arvicola* and a seed identified by Dr. West as the Yellow Water Lily, *Nuphar luteum*. Dr. West said that the West Runton section of the Upper Freshwater Bed of the Cromer Forest Bed Series was one of the most important interglacial sites in north-west Europe. It was the type site for the Cromerian Interglacial. He pointed out that, in his opinion, the term 'interglacial' implied a climatic cycle from cold to warm to cold, a climatic optimum being reached which was comparable in degree to the Post-Glacial climatic optimum. Such a climatic cycle had been found at Hoxne, and pollen analyses of the Upper Freshwater Bed at West Runton by Professor Thomson and more recent and more detailed work by Dr. Duigan had given evidence of a similar climatic cycle. The vegetational changes shown by the analyses were demonstrated on a chart. For these reasons, Dr. West preferred to consider the Upper Freshwater Bed an interglacial deposit, although no true glacial deposits had been found beneath the bed. But it should be recalled that glacial deposits older than the Cromerian Interglacial had been described on the Continent.

Dr. West said that the flora of the Cromer Forest Bed Series was remarkable for the small percentage of plants found in it which are not native to the country at the present time, even though the deposit is early Middle Pleistocene. Such exotics include a water fern (*Azolla*), the water chestnut (*Trapa natans*) and the spruce (*Picea abies*). Finally he pointed out that only in the Upper Freshwater Bed had the pollen been studied analytically, and the importance of Clement Reid's other divisions of the Cromer Forest Bed Series, the Estuarine Bed and the Lower Freshwater Bed, was not known.

Not far to the west of West Runton Gap the party was shown an intensely chalky till which comes in over the Corton Beds at the top of the cliff, and the statement was made that this would be seen better in section on the following day. Finally at West Runton Gap itself, especially on the eastern corner of the gap, a thin gravel was pointed out which caps the top of the cliff and cuts across the top of all the glacial contortions and is therefore later than them. This was described as the gravel from which Mr. Savin and others had obtained Acheulian 'hand-axes'.

The erosion of the cliffs here was stated to average about one yard per year although very irregular in practice. An account was given of how a certain Mr. Cutler carved his name and date on an enormous granite boulder which was in the base of the cliff section in 1770; this huge erratic is now near low-water mark, and Mr. Sainty's latest measurement of its distance from the present base of the cliff is 170 yards.

Friday, 22 August

This day was devoted to a study of the glacial features of the north Norfolk coast, and to an examination of some of the deposits which form the basis of these features. The first section visited was the Briton's Lane gravel pit, in the Cromer Ridge south of Beeston Regis (63/168416). About forty feet of glacial outwash gravel were visible, and Mr. Baden-Powell said that the materials in the gravel, including many igneous and metamorphic rocks in addition to many varieties of flint, seem to be derived from the North Sea Drift, although they may have been deposited at the time of the Lowestoft glaciation: he said that the relation of this gravel to the Corton Beds is not known for certain, but there is some evidence that the Corton Beds are the older of the two. Finally the discovery of a Palaeolithic flint industry in these glacial beds was mentioned.

The party found a great variety of erratics, including a very dark red sandstone (possibly Old Red Sandstone), rhomb porphyry, hornblende syenite (probably Norwegian) and many schists. A new record was then made for this glacial gravel by the discovery by Mr. Larwood of shell fragments, which Mr. Cambridge has identified as: *Cardium* sp., *Cyprina islandica* and *Tellina balthica*. One or two flint flakes which were considered to be humanly struck were also picked up.

The party then proceeded to the cross-roads south of Sheringham known as Pretty Corner (63/151414), where Dr. West distributed sketch-maps showing the main topographical features of the Cromer Ridge (West, 1957, 24). He pointed out that in assessing how fresh the topography appeared it was necessary to separate depositional and erosional features. He did not consider that the whole of the Cromer Ridge showed the same maturity of form. Towards the east, as seen in the northwards view at Pretty Corner, the gravel features were disfigured by the formation of small steep valleys, whilst to the west, as at Telegraph Hill, there was no great development of such valleys. He suggested that the valleys were periglacial in origin, forming under permafrost conditions when rapid erosion of normally permeable deposits would occur during the frequent and periodic melting of surface snow and ice.

On the way to examine more glacial features farther westward, a short stop was made at the Weybourne Town Pit, east of the church (63/115432). Here an intensely chalky till is exposed which contains included streaks of reconstructed North Sea Drift and also derived marine material which is believed to have come from the Corton Beds. This till was correlated with the Lowestoft Till seen in the cliff section at West Runton on the previous day, and fragments of *Cardium edule*, *Tellina balthica* and *Mya* sp. were found.

The party then proceeded to Kelling Heath (63/104425), where a short walk was taken to the top of Telegraph Hill. Dr. West said that he considered Kelling Heath to be a good example of an outwash plain. Telegraph Hill was the highest and most northerly part of the plain and seemed to form the proximal apex of the outwash plain. In contrast to the view at Pretty Corner, the steep ice-contact northern slope of the plain was not deeply dissected by small steep valleys, although a few did occur, and this suggested that the outwash plain belonged to a later episode of glaciation than that which deposited the gravels farther east, e.g. those at Briton's Lane. The curious course of the upper part of the River Glaven was perhaps related to the outwash plain. This river turned abruptly north to the south of Holt, and there is some suggestion that the upper part originated as a river draining the distal part of the outwash plain.

After lunch at Salthouse, the party proceeded to Salthouse Heath, where a short walk was taken north of the Heath. Dr. West explained the two north-west-pointing parallel hills, the Hangs and Scrib Hill, as kames marginal to a small ice-lobe, with Salthouse Heath as the lobe's outwash plain to the south. He said that though these end-moraine features appeared fresh, there was a remarkable absence of kettle-holes in the area, a fact which must be related to the mode of advance and retreat of the ice. It was pointed out that south of Salthouse Heath is a valley running south-west into the Glaven Valley, parallel to the upper part of the Glaven south of the Kelling outwash plain. Possibly this tributary also originated as a drainage stream of the Salthouse outwash plain.

The excursion then proceeded to Wiveton Downs at the eastern end of the Blakeney Esker (63/033421). Here Dr. West said that the Glaven Valley, from Cley to Letheringsett, showed a most interesting series of glacial features. Kame terraces occurred on both sides, related to a lobe of ice once in the valley. The Blakeney esker was a feature parallel to these terraces, but farther north in the more open mouth of the valley. The esker showed the course of a near-marginal channel draining the ice-front. A study of the bedding within it should give the direction of water drainage from the ice lobe in the Glaven Valley. There was some indication that the water flowed back from the ice-front into what is now the North Sea, and this might explain the absence of any marked overflow features in the watershed in the southern part of the Glaven drainage basin. The gravel which forms the Blakeney Esker was seen to be made largely of battered rounded flints, with very few erratics other than flint, a distinction from the older glacial gravel seen at Briton's Lane earlier in the day.

Whilst looking at the excellent view of the Blakeney Shingle Bank from the top of the Blakeney Esker, Mr. Baden-Powell told the party of the intensive work done by Professor Steers and others on the evolution of this part of the coast, and how recent experiments on the movement of artificial radioactive pebbles seemed to support Professor Steers's contention that some of the shingle is brought up to the beach from deeper parts of the sea-bottom. The suggestion was made that it is probable that some of the shingle is also brought from the cliffs between Sheringham and Weybourne, as the main carry of shingle along here is known to be from east to west between tidemarks.

Saturday, 23 August

This day was spent towards the western end of the north coast, to examine the evidence for the latest or Hunstanton glaciation. Two sections were seen, one on either side of the mouth of the River Stiffkey (53/991442) and (53/987441), which showed a little brown Hunstanton Till resting on rounded flint shingle which Solomon had described as a raised beach. Professor Wooldridge and others accepted the shingle as a marine deposit; others in the party were more doubtful. The erosion by the small Stiffkey stream later than this till was pointed out, and the suggestion was made by one member of the party that the mouth of this valley might be a small glacial marginal drainage feature.

The party next visited the Holkham brickworks (53/863428), where better sections in the Hunstanton Till were visible than at the Stiffkey River, especially towards the east end of the Holkham pit. Dr. West pointed out that the brown till here was correlated by Jukes-Browne with the Hessle Boulder Clay of East Lincolnshire and East Yorkshire. This correlation seemed a reasonable one and recent work indicated that the sheet of the Hessle–Hunstanton Tills was deposited by an early advance of the Last (Weichsel) Glaciation, the ice of which extended as a lobe into the Wash and adjacent parts of the Fenland. The party was shown that many Scottish erratics occur here, but that pieces of chalk are rather scarce.

Finally the Ringstead Valley, south of Hunstanton Park, was visited, the coach driving in by the eastern end of the valley (53/706400). The party were able to examine this amazing dry valley and the Hunstanton Park esker in some detail. Dr. West said that the esker was associated with the marginal drainage system of the Hessle–Hunstanton Glaciation. The freshness of the feature was evidence of the Last Glaciation age of the Hessle–Hunstanton deposits. Although the gravel pit which used to be visible at the southern end of the esker is now grassed over, interesting erratics typical of the Hunstanton Till were found on the surface of the esker, including rhomb porphyry, Carboniferous Limestone and a schistose granite; a rock resembling markfieldite was also found.

Sunday, 24 August

The last day was spent in travelling from Norwich to Cambridge, with a visit to the Nar Beds and the March Gravels on the way. The stop in the Nar Valley was at the large gravel pit about one mile east of Blackborough End (53/683146), where Miss Ann Stevens gave an account of her discoveries concerning the stratigraphy and age of the Nar Beds (Miss Leonora A. Stevens, 1959, 28). She said that in the Nar Valley there occurred a series of Pleistocene deposits—a lower till, correlated with the Lowestoft Till, freshwater and estuarine interglacial deposits, and a series of gravels and sands which overlapped the interglacial deposits, ascribed to the Gipping Glaciation. Miss Stevens showed a pollen diagram of analyses from the interglacial deposits and said that the vegetational succession was comparable to that of the Hoxnian Interglacial, so that a correlation between these two was suggested. The occurrence of estuarine freshwater beds gave evidence of a marine transgression during the interglacial. Mr. Baden-Powell said that his study of the marine mollusca of the Nar Beds is not yet finished, but so far the fauna seems like that of the Clacton Channels in Essex, though the two are not identical. Miss Stevens also said that shelly deposits had been found up to about eighty feet O.D. by Rose, which suggested a minimum transgression to about ninety to one hundred feet O.D.

The party examined the cannon-shot gravels at the Blackborough End gravel pit, deposited during the Gipping Glaciation. In the south-east corner of the pit were seen contorted freshwater deposits, part of the interglacial sequence, underlying the sands and gravels. The party then moved on to a section in a drainage ditch (53/688142), south-east of the gravel pit, where interglacial peat was seen to be overlaid by shelly estuarine clay, the Nar Valley Clay. Finally a section was examined some 100 yards north of the main gravel pit which showed a decalcified gravel and sand. Miss Stevens suggested, on the basis of stone orientation measurements, that Gipping Till occurred in this section.

The last place visited before returning to Cambridge was Graysmoor (53/414008), two miles north of March, Cambridgeshire. A little shelly March Gravel was seen here, but unfortunately there was no evidence of any overlying or underlying beds on this occasion. The main shells found were the common forms *Tellina balthica* and *Buccinum undatum*. Mr. Baden-Powell said that when more pits were open years ago it was possible to collect quite a large fauna from the March Gravel, which had a few cold indicators (unlike the Nar Beds) and *Corbicula fluminalis*, normally a freshwater shell, was extremely abundant in some of the March sections and seemed to have adapted itself to life with a marine fauna. The erratics in the March Gravel were derived from the Gipping, and in fact the marine bed had been reported by the Geological Survey as resting on what we now know as Gipping Till. The implements consist of Clactonian and Levallois types, mixed with rare Acheulian. A stony brickearth seen over the March Gravel in some sections has been correlated with the Hunstanton Till.

The party finally returned to Cambridge in the afternoon. Speeches of thanks to the Directors and Secretary had been made by Professor Wooldridge and Mr. Nicholas, and replies had been made by Mr. Baden-Powell and Mr. Spencer.

REFERENCES

Baden-Powell, D. F. W. 1944. On the Occurrence of Hessle Boulder Clay at Happisburgh, Norfolk, containing a Flint Core. *Geol. Mag.*, **81**, 211–2.

———. 1948. The Chalky Boulder Clays of Norfolk and Suffolk. *Geol. Mag.*, **85**, 285.

BADEN-POWELL, D. F. W. 1950. Field Meeting in the Lowestoft District. *Proc. Geol. Ass., Lond.*, **61,** 193–7.

BELL, A. 1911. On the Zonal Stratification of the Eastern British Pliocenes. *Essex Nat.*, **16,** 296.

BOSWELL, P. G. H. 1931. The Stratigraphy of the Glacial Deposits of East Anglia in Relation to Early Man. *Proc. Geol. Ass., Lond.*, **42,** 87–111.

————. 1933. The Contacts of Geology: The Ice Age and Early Man in Britain. Presidential Address, Section C. *Rep. Brit. Ass.* (1932), York, 57–88.

————. 1937. Problems of the Borderland of Archaeology and Geology in Britain. *Proc. prehist. Soc.*, N.S. **2,** 149–60.

————. 1952. The Pliocene–Pleistocene Boundary in the East of England. *Proc. Geol. Ass., Lond.*, **63,** 301–15.

GREEN, C., G. P. LARWOOD & A. J. MARTIN. 1953. The Coastline of Flegg. *Trans. Norfolk Norw. Nat. Soc.*, **17,** 336.

HARMER, F. W. 1900. On a Proposed New Classification of the Pliocene Deposits of the East of England. *Rep. Brit. Ass.* (1899), Dover, 751.

LONGFIELD, T. E. 1933. Subsidence of London. *Proc. geol. Soc. Lond.*, **1260,** 73.

SPENCER, H. E. P. 1951. Geological Records. *S.-East. Nat.*, **55,** xxvi.

STEERS, J. A. 1926. Orford Ness: A Study in Coastal Physiography. *Proc. Geol. Ass., Lond.*, **37,** 306.

STEVENS, LEONORA A. 1959. The Interglacial of the Nar Valley. *Proc. geol. Soc. Lond.*, **1565,** 28.

WATT, A. S. 1955. Stone Stripes in Breckland, Norfolk. *Geol. Mag.*, **92,** 173.

WEST, R. G. 1956. The Quaternary Deposits at Hoxne. *Phil. Trans.*, B., **239,** 265.

———— & J. J. DONNER. 1956. The Glaciations of East Anglia and the East Midlands: A differentiation based on stone-orientation measurements of the tills. *Quart. J. geol. Soc. Lond.*, **112,** 83.

————. 1957. Notes on a Preliminary Map of some Features of the Drift Topography around Holt and Cromer, Norfolk. *Trans. Norfolk Norw. Nat. Soc.*, **18,** 24.

The Annual Report of the Council of the Geologists' Association for the year 1959

MEMBERSHIP

THE numerical strength of the Association on 31 December 1959, was as follows:

Honorary Members	21	(23)
Ordinary Members:		
Life Members (compounded)	173	(181)
Annual Subscribers	1863	(1819)
Institutional Members	55	(52)
	2112	(2075)

(Corresponding figures for 31 December 1958 in brackets)

During the year 176 new members were elected, and the Association lost 140 members through death, resignation and removal under Rule XI for failure to pay subscriptions. One member was reinstated.

The list of deceased members is as follows:

J. K. Allen, F. J. Barton, Mrs. A. Bolitho, E. Ernest S. Brown, H. J. W. Brown, S. C. Chin Hong, W. Cocksedge, A. Morley Davies, Rev. J. Fowler, Miss E. Goodyear, H. W. Greenwood, A. Howell, Miss C. F. Marshall, G. A. Peet, L. J. Spencer, Mrs. U. C. M. Strickland, Mrs. L. Treacher, W. D. Ware, W. G. Weeks, A. S. Williams, C. B. Wilson, C. L. Woodhouse, C. E. Worthington, J. W. Wright, B. O. Wymer. (J. J. Hartley, a former member.)

HOUSE LIST

The following retirements are announced:

Professor David Williams, as the Centenary Year President, Dr. A. J. Dollar, as Senior Vice-President, Dr. Janet Watson, who has been acting as Secretary to the Publications Committee in place of Dr. Ager, and Messrs. Hester, Pitcher and Peake as ordinary members of Council. Thanks are due to these members for valuable services rendered to the Association.

FINANCE

The year ended with a deficit on the General Purposes Fund of £80 16*s*. 8*d*. compared with an opening deficit of £53 18*s*. 8*d*. Income was higher than in 1958 by about £600, due mainly to an increase of £475 in dividends. This additional income permitted an increased expenditure of £500 on the PROCEEDINGS. Other increases in income were £100 from subscriptions, £50 from the sale of publications, and £50 from the Illustrations Fund. On the expenditure side there were increases in the cost of monthly Circulars and on postage; a liability of £200 was incurred for the typesetting of a new List of Members.

During the year the Funds for Special Purposes have been rearranged. The Centenary Fund was closed and the receipts and expenditure on the Centenary Guides segregated in a separate Centenary Guides Fund. After this separation the Centenary Fund showed a credit balance, which, together with the credit balance of the Watts Charnwood Forest Fund, were transferred to the Centenary Guides Fund as initial working capital; the balance of the net expenditure on Guides has been met by an advance from the capital of the Bequest Fund.

The Johnston and Howarth Fund has been absorbed by the Bequest Fund, to which has also been transferred the capital of the Illustrations Fund; but the latter Fund will remain open for current donations. The holding of shares in Currys Ltd. has been placed in a separate Fund, to mark the special intention that, in accordance with the expressed wishes of the donor, the shares should continue to be held and the income used for the current purposes of the Association.

The total capital invested in Guides at 31 December 1959 was £1024 6*s*., which should eventually be repaid from the proceeds of sales, which up to the present have been encouraging.

A new Compounding scheme was announced in Circular No. 615.

Rising costs, especially of printing and postage, in recent years have had a serious effect on the Association's finances, and caused a drastic reduction in the size of the PROCEEDINGS in 1958. During 1959 it became clear that there would be further increases in printing costs, and the Council very reluctantly decided that it must ask Members to agree to an increase in the Annual Subscription. A Resolution to increase the Annual Subscription to £2 was passed at the Special General Meeting held on 5 June 1959. The Council believes that despite the increase, the Subscription gives Members very good value, and is confident that this will be enhanced when the measures they are taking to improve the PROCEEDINGS materialise.

Balance Sheet at 31 December 1959

Statement 1

1958		CAPITAL Invested	CAPITAL Uninvested	REVENUE	TOTAL
£		£ s. d.	£ s. d.	£ s. d.	£ s. d.
	FUNDS FOR SPECIAL PURPOSES:				
	Bequest Fund	2821 14 0	346 7 7		3168 1 7
	Curry Fund	2500 0 0			2500 0 0
	Compounding Fund	2407 9 7	89 15 0		2497 4 7
	TRUST FUNDS:				
	Foulerton Award Fund	294 11 0		16 10 10	311 1 10
	Henry Stopes Memorial Fund ...	260 12 9		26 7 2	286 19 11
	G. W. Young Geological Investigation Fund			47 10 11	47 10 11
9172		8284 7 4	436 2 7	90 8 11	8810 18 10
	GENERAL FUNDS:				
142	Subscriptions paid in advance ...				183 11 4
211	Sundry Creditors				257 16 1
	Estimated Accrued Expenditure:				
500	Printing and Postage of Part 4 of PROCEEDINGS				400 0 0
35	Printing Monthly Circular ...				35 0 0
—	Printing List of Members ...				200 0 0
13	Reserve for Index of PROCEEDINGS				12 16 4
					£9900 2 7

1958		£ s. d
£		
8064	Investments	8284 7 4
28	Income Tax Recoverable	187 19 9
550 *Overdrawn*	Cash at Bank	1121 9 5
19	Petty Cash in hands of officers	30 17 11
—	Proceeds of sales of G.A. Guides by Editor not paid in	54 11 6
60	Estimated Accrued Income from Advertising	40 0 0
125	Estimated Value of Arrears of Subscriptions (Book Value £258 17*s.* 3*d.*)	100 0 0
54	Deficit on Income and Expenditure Account	80 16 8
		£9900 2 7

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31 DECEMBER 1959

Statement 2

EXPENDITURE

1958 £			£ s. d.	£ s. d.
477	DEFICIT AT 31 DECEMBER 1958 BROUGHT FORWARD			53 18 8
1070	PRINTING 'PROCEEDINGS' OF THE ASSOCIATION: (including £350 for Estimated Additional Expenditure for Part 4 of Vol. 70)			1582 2 0
	GENERAL EXPENSES:			
45	Meetings		38 13 8	
302	Printing Monthly Circular (including accrued expenditure of £35)		405 0 9	
161	Printing and Stationery		182 11 7	
	Postages:			
	PROCEEDINGS (including £50 Estimated Additional Expenditure)	299 7 4		
	Circulars	172 2 6		
	Miscellaneous	48 12 2		
307			520 2 0	
31	Typing and Duplicating		59 4 9	
20	Binding Volumes of PROCEEDINGS		— — —	
—	Purchase of past issues of PROCEEDINGS ...		20 7 6	
—	Printing List of Members, estimated accrued expenditure		200 0 0	
9	Incidental Expenses		19 17 11	
				1445 18 2
				£3081 18 10

INCOME

1958 £		£ s. d.	£ s. d.
1735	ANNUAL SUBSCRIPTIONS: (Including £100 being estimated value for book arrears of £258 17*s*. 3*d*. at 31 December 1959)	1837 8 5	
96	ADMISSION FEES	90 0 0	
93	INCOME FROM ADVERTISEMENTS (including estimated accrued income of £40)	49 14 7	
293	SALES OF PUBLICATIONS (other than *The History of the Geologists' Association* and G. A. Guides)	342 15 2	
32	INCOME FROM ILLUSTRATIONS FUND	86 7 8	
45	INCOME FROM BEQUEST FUND	37 13 2	
74	INCOME FROM COMPOUNDING FUND	82 3 2	
—	INCOME FROM CURRY FUND	475 0 0	
			3001 2 2
54	DEFICIT AT 31 DECEMBER CARRIED FORWARD ...		80 16 8
			£3081 18 10

FUNDS FOR SPECIAL PURPOSES

CENTENARY FUND

Statement 3

	£	s.	d.		£	s.	d.
Debtor Balance at 1 January 1959	750	17	6	INCOME:			
				Interest from Investments	21	16	4
				Sales of *History of the Geologists' Association*	23	19	2
TRANSFERS TO THE CENTENARY GUIDES FUND:				TRANSFER TO THE CENTENARY GUIDES FUND:			
Income from sale of Guides in 1958	200	14	0	Expenditure on Guides in 1958	1247	3	7
Balance of Centenary Fund at 31 December 1959	341	7	7				
	£1292	19	1		£1292	19	1

(Fund closed)

CENTENARY GUIDES FUND

Statement 4

Income and Expenditure Account

	£	s.	d.		£	s.	d.
TRANSFER FROM CENTENARY FUND:				TRANSFER FROM CENTENARY FUND:			
Expenditure on Guides in 1958	1247	3	7	Income from sales of Guides in 1958	200	14	0
EXPENDITURE:				INCOME:			
Printing of three G. A. Guides	309	12	4	Sales of Guides in 1959	331	15	11
				Balance at 31 December 1959	1024	6	0
	£1556	15	11		£1556	15	11

Working Capital Account

	£	s.	d.		£	s.	d.
Balance of Income and Expenditure Account at 31 December 1959	1024	6	0	INITIAL CAPITAL:			
				Balance of Centenary Fund at 31 December 1959	341	7	7
				Balance of Watts Charnwood Forest Fund at 31 December 1959	187	15	2
				Advance from Bequest Fund	495	3	3
	£1024	6	0		£1024	6	0

FUNDS FOR SPECIAL PURPOSES (*Continued*)

BEQUEST FUND

Statement 5

	Investments £ s. d.	Uninvested Capital £ s. d.	Revenue £ s. d.
Transfer to Curry Fund	2500 0 0		
Transfer to Income and Expenditure Account			37 13 2
Sale of Investment	285 0 0		
New Investment		459 18 5	
Advance of Capital to Centenary Guides Fund		495 3 3	
Balances at 31 December 1959	2821 14 0	346 7 7	
	£5606 14 0	£1301 9 3	£37 13 2

	Investments £ s. d.	Uninvested Capital £ s. d.	Revenue £ s. d.
Balances at 1 January 1959	3626 14 0	162 13 0	
Investment Income			37 13 2
Bequests		12 5 5	
Sale of Investment		285 0 0	
New Investment	459 18 5		
Transfer from Illustrations Fund ...	120 0 0		
Transfer from Johnston and Howarth Fund (Capital)	1400 1 7	580 1 6	
Transfer from Johnston and Howarth Fund (Revenue)		261 9 4	
	£5606 14 0	£1301 9 3	£37 13 2

CURRY FUND

Statement 6

	Invested Capital £ s. d.	Revenue £ s. d.
Transfer to Income and Expenditure Account ...		475 0 0
Balance at 31 December 1959	2500 0 0	
	£2500 0 0	£475 0 0

	Invested Capital £ s. d.	Revenue £ s. d.
Transfer from Bequest Fund	2500 0 0	
Investment Income		475 0 0
	£2500 0 0	£475 0 0

COMPOUNDING FUND

Statement 7

	Investments £ s. d.	Uninvested Capital £ s. d.	Revenue £ s. d.
Transfer to Income and Expenditure Account			82 3 2
New Investment		140 0 0	
Balances at 31 December 1959	2407 9 7	89 15 0	
	£2407 9 7	£229 15 0	£82 3 2

	Investments £ s. d.	Uninvested Capital £ s. d.	Revenue £ s. d.
Balances at 1 January 1959	2267 9 7	16 0 0	
Investment Income			82 3 2
Compounding Fees Received		213 15 0	
New Investment	140 0 0		
	£2407 9 7	£229 15 0	£82 3 2

FUNDS FOR SPECIAL PURPOSES (*Continued*)

ILLUSTRATIONS FUND

Statement 8

	Invested Capital £ s. d.	Revenue £ s. d.		Invested Capital £ s. d.	Revenue £ s. d.
Transfer to Income and Expenditure Account ...		86 7 8	Balance at 1 January 1959	120 0 0	
Transfer to Bequest Fund	120 0 0		Investment Income		5 9 2
			Donations and Subscriptions		80 18 6
	£120 0 0	£86 7 8		£120 0 0	£86 7 8

WATTS CHARNWOOD FOREST FUND

Statement 9

	£ s. d.		£ s. d.
Transfer to Centenary Guides Fund	187 15 2	Balance at 1 January 1959	185 3 6
		Sales	2 11 8
	£187 15 2		£187 15 2

(Fund Closed)

JOHNSTON AND HOWARTH FUND

Statement 10

	Investments £ s. d.	Uninvested Capital £ s. d.	Revenue £ s. d.		Investments £ s. d.	Uninvested Capital £ s. d.	Revenue £ s. d.
Sale of Investments	495 0 0			Balances at 1 January 1959	1495 0 0	455 8 7	205 9 7
Bank charge on Sale of Investment ...		1 2 4		Investment Income			55 19 9
New Investment		400 1 7		Post War Credits (Howarth Estate) ...		30 16 10	
Transfer to Bequest Fund	1400 1 7	580 1 6	261 9 4	Sale of Investments		495 0 0	
				New Investment	400 1 7		
	£1895 1 7	£981 5 5	£261 9 4		£1895 1 7	£981 5 5	£261 9 4

(Fund Closed)

TRUST FUNDS

FOULERTON AWARD FUND

Statement 11

	£	s.	d.		£	s.	d.
Award to J. N. Carreck	10	0	0	Balance at 1 January 1959	16	1	2
Balance at 31 December 1959	16	10	10	Investment Income	10	9	8
	£26	10	10		£26	10	10

HENRY STOPES MEMORIAL FUND

Statement 12

	£	s.	d.		£	s.	d.
Balance at 31 December 1959	26	7	2	Balance at 1 January 1959	18	7	8
				Investment Income	7	19	6
	£26	7	2		£26	7	2

G. W. YOUNG GEOLOGICAL INVESTIGATION FUND

Statement 13

	£	s.	d.		£	s.	d.
Balance at 31 December 1959	47	10	11	Balance at 1 January 1959	35	9	7
				Income from Public Trustee	12	1	4
	£47	10	11		£47	10	11

Statement 14

Schedule of Investments—31 December 1959

	AT COST OR PAR VALUE WHEN ACQUIRED				INVESTMENT INCOME (GROSS)		
	£	s.	d.		£	s.	d.
NDS FOR SPECIAL PURPOSES:							
Bequest Fund:							
£143 8 9 3½% War Stock	141	14	0		5	0	6
£100 3% Savings Bonds 1960/70	100	0	0		3	0	0
£441 5 4 3% British Transport Guaranteed Stock 1978/88	400	0	0		13	4	9
£224 13 3 4½% British Electricity Guaranteed Stock 1974/79	200	0	0		9	11	0
£806 9 0 6% Newcastle-on-Tyne Stock 1973/76	860	0	0	New Investment	Nil		
				Income from Investments sold during the year: £85 3% Defence Bonds	1	10	6
				£200 3½% Defence Bonds	5	6	5
Illustrations Fund:					£37	13	2
(transferred to Bequest Fund)							
£21 0 10 3% Metropolitan Water Board 'B' Stock	20	0	0			12	6
£113 13 1 4½% British Electricity Guaranteed Stock 1974/79	100	0	0		4	16	8
					£5	9	2
Johnston and Howarth Fund:							
(transferred to Bequest Fund)							
£1236 4 6 3½% War Stock	1000	0	0		43	5	4
				Income from Investment sold during the year: £495 4½% Defence Bonds	12	14	5
					£55	19	9
Total, Bequest Fund	2821	14	0				
Curry Fund:							
10,000 Shares Curry's Ltd. par value	2500	0	0		475	0	0
Centenary Fund:				Income from Investment sold during the year: £1000 4½% Defence Bonds	21	16	4
Compounding Fund:							
£1217 2 6 3% Irredeemable Nottingham Corporation	1152	13	2		36	10	2
£200 3% Savings Bonds 1955/65	200	0	0		6	0	0
£170 3½% War Stock	152	14	5		5	19	0
£100 3% Savings Bonds 1965/75	100	0	0		3	0	0
£300 3½% Treasury Stock 1977/80	282	2	0		10	10	0
£224 13 3 4½% British Electricity Guaranteed Stock 1974/79	200	0	0		9	11	0
£177 11 4 6% New Zealand Stock 1976/80	180	0	0		10	13	0
£131 4 6 6% Newcastle-on-Tyne Stock 1973/76	140	0	0	New Investment	Nil		
	£2407	9	7		£82	3	2
RUST FUNDS:							
Foulerton Award Fund:							
£349 7 0 3% British Transport Guaranteed Stock 1978/88	294	11	0		10	9	8
Henry Stopes Memorial Fund:							
£265 19 2 3% Newfoundland Stock 1943/63	260	12	9		7	19	6

J. CARMICHAEL, *Hon. Accountant.*

We have compared these Statements with the books and records presented to us and find them to agree. We have also verified the Investments and Cash Balances held by the Association at 31 December 1959.

. M. MONTFORD, *Treasurer*
February 1960.

F. J. W. HOLWILL
F. A. MIDDLEMISS } *Auditors.*

REPORT OF THE SESSION 1959

TRUSTEES

The Trustees of the Association were:

Managing: Dr. W. F. Fleet, M.SC., A.R.I.C., A.C.P., F.G.S., Mr. Percy Evans, M.A., F.G.S., and Dr. W. A. Macfadyen, M.C., M.A.

Custodian: The Royal Bank of Scotland, Western Branch.

PUBLICATIONS

Publications Committee. The Committee consisted of the seven officers with Dr. Janet Watson and Messrs. H. W. Ball, D. Curry, J. Sutton, S. C. A. Holmes and J. F. Kirkaldy. Dr. Watson acted as secretary up till October, when Dr. D. V. Ager took over again on his return from the U.S.A.

The Committee met on eight occasions and considered twenty-seven papers, of which twenty-one were recommended for publication.

Proceedings. Part 4 of Volume 69 was published in February. This consisted of 82 pages and two plates, making a total of 273 pages and four plates for the volume.

The first three parts of Volume 70 were published during the year. These contained 272 pages and three plates. The fourth part will be published early in 1960.

MEETINGS

Nine Ordinary Meetings and three Special General Meetings were held, at which six papers were read, six papers taken as read and three lectures were given. Professor David Williams (President) took the Chair at all these meetings except the one held on 3 April when Mr. C. W. Wright (Vice-President) was in the Chair.

The thanks of the Association are due to the lecturers, to the authors of papers and to the Geological Society for use of its apartments throughout the year.

The names of the 176 members elected in 1959 appeared in Circulars numbered 609–618.

2 *January*. Paper: 'A Contribution to the Geomorphology of Central Donegal', by G. H. Dury.

Special General Meeting (see Circulars Nos. 608 and 609).

6 *February*. Paper: 'The North-West Border of the Dartmoor Granite', by W. R. Dearman and N. E. Butcher.

6 *March*. Annual General Meeting followed by Ordinary Meeting.

3 *April*. Paper: 'The Origin and Development of Karstic Depressions in the Mendip Hills', by A. Coleman and W. G. V. Balchin. Papers read in title only: 'A New Inarticulate Brachiopod from the Dorset Corallian', by D. V. Ager. 'The Rhaetic of the Bridgend District, Glamorganshire', by E. H. Francis. 'The Superficial Deposits of the Buried Valley of the River Devon near Alva, Clackmannan, Scotland', by A. Parthasarathy and F. G. H. Blyth. 'Some Observations on the Antrim Basalts and Associated Dolerite Intrusions', by G. P. L. Walker.

1 *May*. Lecture: 'The Geology of Leonardo da Vinci', by R. Bradshaw.

5 *June*. Special General Meeting (see Circulars Nos. 613 and 614).

Ordinary Meeting. Paper: 'Palaeocurrents and Sedimentary Facies of the Dalradian Metasediments of the Craignish–Kilmelfort District', by J. L. Knill. Papers read in title only: 'The Old Red Sandstone of the Cleobury Mortimer Area, Shropshire', by D. L. Dineley and D. W. Gossage. 'Frost-heaved Soils of Barrow, Rutland', by L. F. Curtis and J. H. James. 'An Interglacial Tufa near Hitchin, Hertfordshire', by M. P. Kerney.

3 *July*. Papers: (a) 'The Tectonics of the "Great Ice Chasm", "Filchner Ice Shelf", Antarctica', by Gilbert Wilson. (b) 'Dedolomitisation of some Mesozoic Limestones from the French Jura', by D. J. Shearman, J. N. Khouri, and the late M. S. M. Taha.

16 *October*. Special General Meeting (see Circulars Nos. 615 and 616). Lecture: 'A Geological Excursion down the Grand Canyon', by Dr. D. V. Ager.

14 *November*. Ordinary meeting followed by the Reunion (for list of exhibits see page 97).

4 *December*. Lecture: 'How to Identify Fossils', by Dr. J. E. Prentice.

At the January meeting Dr. H. W. Ball and Mr. F. J. W. Holwill were elected auditors of the Association's Accounts for 1958.

The Annual General Meeting was held on 6 March 1959, Professor D. Williams, President, in the Chair.

The Annual Report of the Council (previously circulated) was taken as read. It was proposed by Mr. J. E. Guest and seconded by Mr. P. G. Weighton and duly carried, 'That the Report of the Council, including the Statement of Accounts, be adopted as the Annual Report of the Association for the year 1958'.

The President declared the following members duly elected as Officers and Members of Council in accordance with Rule XIII: *President*, David Williams, D.SC., Ph.D., M.I.M.M., F.G.S.; *Vice-Presidents*, A. J. Dollar, B.SC., Ph.D., A.K.C., F.R.S.E., F.G.S., D. Curry, M.A., F.G.S., A. K. Wells, D.SC., F.G.S., C. W. Wright, M.A., F.G.S., L. J. Pitt, F.G.S.; *Treasurer*, H. M. Montford, O.B.E., B.SC.; *Secretaries*, General—F. H. Moore, B.SC., Ph.D., F.G.S.; Field Meetings—J. M. Hancock, M.A., Ph.D., F.G.S.; Publications

Committee—J. V. Watson, B.SC., Ph.D., A.R.C.S., F.G.S. (Acting); *Editor*, G. T. Raine, B.SC., A.M.Inst.Pet., F.G.S.; *Librarian*, A. J. Smith, B.SC., Ph.D., F.G.S.; *Twelve other Members of Council*, S. W. Hester, F.G.S., W. S. Pitcher, Ph.D., B.SC., D.I.C., F.G.S., N. B. Peake, F.G.S., M. K. Wells, M.SC., Ph.D., F.G.S., Mrs. J. N. Carreck, G. F. Elliott, F.G.S., John Sutton, Ph.D., A.R.C.S., F.G.S., Miss M. A. Arber, M.A., F.G.S., F.R.G.S., Mrs. M. Ainsley, F.G.S., Miss M. M. Sweeting, M.A., Ph.D., C. F. Tozer, B.SC., Ph.D., D.I.C., F.G.S., D. G. A. Whitten, B.SC., A.R.C.S., F.G.S.

It was proposed by Mr. N. D. Corps and seconded by Mr. Ragg and duly carried, 'That the best thanks of the Association be given to the Officers, retiring Members of Council and the Auditors'.

The Foulerton Award and Certificate were presented to Mr. J. N. Carreck in recognition of his work for the Geologists' Association.

The President said:

> Mr. Carreck: I am sure that all members of the Association will heartily endorse the Council's decision to present you with this year's Foulerton Award in token of your past services to the Association, and in the hope that you will long continue your fruitful work.
>
> Since you were elected a Member thirteen years ago the exhibits at our Annual Reunions have been enhanced many times by the results of your intense passion for collecting, especially from your favourite areas of Weymouth and south-east London, about which your store of geological knowledge is truly encyclopaedic. You have enriched our PROCEEDINGS, in collaboration with the late A. G. Davis, by accounts of the Quaternary deposits of Bowleaze Cove, near Weymouth, and also by your own descriptions of vertebrate fossils of late Pleistocene age from Levaton in South Devon.
>
> Moreover, you have on several occasions conducted successful Field Meetings of the Association to various places in Kent, including Downe House, and during the Centenary Year you led an excursion to Swanscombe and Northfleet, areas described by you in the Association's Guide to the London Region. In addition, you have taken a lively interest in the history of the Association and have helped to preserve and add to our albums and archives.
>
> Apart from your generous help to the Association you have served the cause of geology well by your altruistic and unobtrusive labours at the Dorset County Museum and recently at the Dartford Museum, where the geological displays are an eloquent testimony to your skill.
>
> Your enthusiasm, competence and constant willingness to help and interest others embody the best traditions of our Association, and in presenting you with this Award we think of you as a worthy successor to such stalwart amateurs as Kennard, Leach, Chandler and Simeon Priest, who were pillars of the Association a generation ago and also recipients of the Foulerton Award.

The President then delivered his address entitled, 'Mineral Exploration'.

It was proposed by Professor S. E. Hollingworth and seconded by Mr. D. G. A. Whitten and duly carried, 'That the best thanks of the Association be accorded the President for his Address'.

FIELD MEETINGS 1959

The Committee consisted of the seven officers with Messrs. D. F. W. Baden-Powell, J. S. H. Collins, S. W. Hester, F. Middlemiss, N. Peake, D. Shearman, Miss M. M. Sweeting and Mr. D. G. A. Whitten.

Four demonstrations, one week-end, nine whole day and two half-day Field Meetings were held during the year.

The Easter Field Meeting was held in the north-west Dartmoor area and the Whitsun Field Meeting held in the Weymouth area. One Summer Long Field Meeting was held in Brittany and another in Snowdonia and Lleyn.

The Association is very grateful to the Directors, Secretaries and all others who helped at these meetings.

The following Field Meetings and Demonstrations took place:

29 *January*. Demonstration at the Photogeological Section of the Overseas Geological Surveys, Tolworth, under the direction of Dr. S. H. Shaw.

21 *February*. Field Meeting in the Maidstone area, directed by the Field Meeting Secretary, being a substitute for a Demonstration at Snowdown Colliery, Kent, which was cancelled at a few hours notice.

14 *March*. Demonstration at the Building Research Station, Watford, at the invitation of the Director.

26–30 *March*. Easter Field Meeting around north-west Dartmoor. Directors, Dr. W. R. Dearman and Mr. N. E. Butcher.

25 *April*. Field Meeting at the new Maidstone By-Pass. Director, Dr. R. Casey.

2 *May*. Field Meeting at the Isle of Sheppey. Director, Mr. G. F. Elliott.

15–18 *May*. Whitsun Field Meeting to Portland, Weymouth and Dorchester. Director, Mr. J. N. Carreck.

30 *May*. Field Meeting at Wrabness and Walton-on-Naze. Director, Mr. H. E. P. Spencer.

6 *June*. Field Meeting at Bayford, Herts. Director, Professor S. W. Wooldridge.

28 *June*. Field Meeting at Eastbourne. Directors, Messrs. J. M. Hancock and N. B. Peake.

19 *July*. Field Meeting at Folkestone. Director, Dr. R. Casey.

8 *August*. A Demonstration in the field of simple geological mapping at Rudgwick, Sussex. Directors, Dr. R. G. Thurrell and Mr. B. C. G. Worssam of the Geological Survey.

4–6 *September*. Field Meeting to study the Cretaceous of north Norfolk. Director, Mr. N. B. Peake.

10–22 *September*. Summer Field Meeting in Brittany. Directors, Professor Y. Milon and Dr. Suzanne Durand.

19–28 *September*. Summer Field Meeting around Snowdonia and Lleyn.

Organising Director, Dr. N. Rast; Directors, Mr. F. J. Fitch, Dr. J. G. Ramsay and the President.

19 *September*. Field Meeting at Grays, Thurrock. Director, Mr. J. McA. Hart.

3 *October*. Field Meeting around Tunbridge Wells. Director, Mr. D. Shearman.

21 *November*. Demonstration of Site Investigation by the staff of Soil Mechanics Ltd.

6 *December*. Field Meeting at Taplow. Director, Mr. J. Wymer.

12 *December*. First of three Demonstrations on Fossil Identification, at the Department of Geology, University of London, King's College. Demonstrators, Dr. R. Goldring (Trilobites), Mr. D. G. Jones (Palaeozoic plant impressions), Mr. J. B. Richardson (Palaeozoic plant spores) and Dr. M. Sudbury (Graptolites).

NORTH-EAST LANCASHIRE GROUP

Chairman, D. H. Learoyd, B.SC., F.G.S.; Vice-Chairman, J. Ranson, A.M.I.Min.E., F.G.S.; Secretary, H. Grieve; Committee, Mrs. J. Ranson, B.A., A. Moore, B.SC., E. Procter, S. Westhead, I. A. Williamson, B.SC., F.G.S.

During the year seven meetings were held and there were five Field Meetings.

16 *January*. 'The Pot-holes and Caves of Ingleborough and Penyghent', by J. Parkinson.

13 *February*. 'Lead Mining in Lancashire', by I. A. Williamson.

13 *March*. 'The Geology of the Barmouth–Cader Idris Area', by J. Ranson.

10 *April*. 'Measuring the Age of Rocks', by D. H. Learoyd.

25 *April*. Field Meeting: 'The Easterly Limb of the Bumley Syncline to the Pennine Anticline', by E. Procter.

9 *May*. Field Meeting: 'The Lower Palaeozoic Rocks of Crummock Dale', by J. Ranson.

13–14 *June*. Field Meeting: 'The East Side of the Duddon Estuary', by W. Grieve.

8 *August*. Field Meeting: 'The Mid-Craven Fault, Malham', by I. A. Williamson.

19 *September*. Field Meeting: 'The Geology of Chapel-le-Dale and Kingsdale, Ingleton', by D. H. Learoyd.

23 *October*. The thirty-sixth Annual General Meeting. Résumés of the Field Meetings were given by the various directors.

13 *November*. 'The Canadian Shield', by J. S. Shackleton.

4 *December*. 'The Great Whin Sill', by J. Ranson.

MIDLAND GROUP

Chairman, W. G. Hardie, B.SC., F.G.S.; Secretary, I. Strachan, B.SC., Ph.D., F.G.S.; Committee, Professor F. W. Shotton, M.B.E., SC.D., F.G.S., Miss G. M. Bauer, J. D. Lawson, Ph.D., F.G.S., W. Tennent, M.D., A. Chater, G. Farrell.

Five indoor meetings and five Field Meetings were held.

31 *January*. Professor D. Williams on 'Prospecting for Minerals'.

28 *February*. Dr. M. J. Frost on 'Modern Gemmology'.

4 *April*. Excursion to Lickey and Upper Malbrook. Director, Mr. Sanders.

1–3 *May*. Week-end visit to Forest of Dean. Director, Dr. Lawson.

7 *June*. Whole-day excursion to Dunchurch and Kilsby (M.1.). Director, Mr. Sanders.

11 *July*. Excursion to Nuneaton. Director, Mr. Garrett.

26 *September*. Excursion to Netherton. Director, Dr. Strachan.

10 *October*. Address by the Chairman, W. G. Hardie, on 'Water Divining'.

7 *November*. Dr. M. J. Frost on 'A Geologist in Western Australia'.

12 *December*. Mr. Garrett on 'Spitsbergen 1958' and Christmas Party.

Thanks are due to Professor F. W. Shotton for the use of the Geology Department, Birmingham University.

NORTH STAFFORDSHIRE GROUP

Professor F. Wolverson Cope, D.SC., M.I.Min.E., F.G.S.

Chairman, C. S. Exley, M.A., D.Phil., F.G.S.; Deputy Chairman, P. S. Keeling, B.SC., A.R.S.M., F.G.S.; Secretary, T. S. Purcell, B.SC., F.G.S.; Treasurer, J. T. Gleaves, B.A.; Field Secretary, T. S. Jones, F.G.S.; Research Secretary, D. O. Thomas, F.G.S.; Committee, M. D. Cox, Dr. M. J. Farrell, A. B. Malkin, B.SC., J. Myers, B.SC., F.G.S., F.R.G.S., J. C. Parrack, B.SC., F.R.G.S.

During the year seven Ordinary Meetings and four Field Meetings were held. The Ordinary Meetings were again held in the Arts Centre, Newcastle under Lyme, but for the Annual Conversazione, on the night of the General Election, we were at Cartwright House, Hanley.

A feature of the Ordinary Meetings throughout the year has been a succession of rewarding discussions, for which thanks go to the authors of stimulating addresses.

The year 1959 also saw the tenth anniversary of the first meeting of the Group, on 24 February 1949.

The following meetings and Field Meetings were held:

8 *January*. Members' Slide and Photo Evening.

12 *February*. W. H. Wilcockson, M.A., F.G.S., on 'The Geology of Kilimanjaro'.

12 *March*. Annual General Meeting. The Chairman on 'Clay Minerals'.

19 *April*. Field Meeting to Wenlock Edge. Director, J. T. Wattison, F.G.S., F.R.E.S.

10 *May*. Field Meeting to Harlech Dome. Director, Dr. C. S. Exley.

14 *May*. Dr. J. D. Lawson on 'The Geology of the Ludlow Area'.

13 *September*. Field Meeting to Breidden Hills. Director, Miss H. Hignett.

8 *October*. Annual Conversazione in Cartwright House, Hanley.

17 *October*. Field Meeting to Roches and Goldsitch Moss.

12 *November*. A. B. Malkin, B.SC., on 'Coal Measures Research'.

10 *December*. Members' Slide and Photo Evening.

JAMAICA GROUP

Chairman, L. J. Chubb, Ph.D., D.SC., F.G.S.; Vice-Chairman, S. A. G. Taylor; Secretary, E. Robinson, B.SC.; Treasurer, H. R. Versey, M.SC.; Editor, J. B. Williams, B.SC.; Committee, Leila Dutt, B.SC., Cecilia Legge, C. B. Lewis, B.A., A. Munoz-Bennett, V. A. Zans, Mag.rer.nat.habil., F.G.S.

During the year there were five Field Meetings and one long excursion, the second run by the Group. Two meetings were also held in addition to the Annual General Meeting and the quarterly magazine of the Group, *Geonotes*, continued publication.

At the Annual General Meeting the Jamaica Group of the Geologists' Association was dissolved and a new society, the Geological Society of Jamaica, was formed, having aims and interests similar to those of the Geologists' Association.

Thanks are due to the Director of the Institute of Jamaica for the use of the Science Library for Committee Meetings.

The following meetings and Field Meetings were held:

25 *January*. Field Meeting: 'The Cretaceous Rocks of the St. Ann's Great River Inlier. Director, L. J. Chubb.

30 *March*–5 *April*. Easter Field Meeting in Clarendon. Directors, J. B. Williams, L. J. Chubb and H. R. Versey.

1 *May*. Lecture: 'Caves and Cave Exploration in Jamaica', by V. A. Zans.

31 *May*. Field Meeting: 'The Judgment Cliff Landslide, St. Thomas.' Director, V. A. Zans.

24 *July*. Lecture: 'Beachrock in the Caribbean', by R. J. Russell.

26 *July* and 2 *August*. Field Meetings at Pigeon Island. Directors, V. A. Zans, R. P. Bengry and H. R. Versey.

27 *September*. Field Meeting: 'The Mining Activities of the Kaiser Bauxite Company.' Director, J. W. Lee.

28 *November*. Field Meeting: 'Newcastle and Silver Hill.' Director, H. R. Versey.

9 *December*. Annual General Meeting, followed by four short films loaned by the Shell Company of Jamaica.

11 *December*. Dinner-Dance at the Courtleigh Manor Hotel.

REUNION

The Annual Reunion was held at the Chelsea College of Science and Technology. It was attended by over 530 members and friends.

Thanks are due to the Principal and Staff of the College and the members concerned.

LIST OF EXHIBITS

British Museum (Natural History)

Department of Palaeontology

(*a*) Some recent advances in Casting Techniques.

(*b*) Incomplete Skeleton of a Small Ichthyosaur from Charmouth, with associated skin fragments.

(*c*) Morphological variations of *Alveolina fusiformis* Sowerby from the Eocene of Bracklesham.

Departments of Mineralogy and Palaeontology

(*d*) Rocks and fossils collected by the British Museum Expedition to South Peru, 1959.

Geological Survey and Museum

(*a*) Fossils from the Maidstone By-pass excavations.

(*b*) Recent publications.

Ager, Dr. D. V.

Fossils, maps and colour slides of the Mesozoic of Hungary.

Anthony, Dr. H. D.

Influence of geology on scenery. Photographs.

Bishop, Dr. A. C. and Dr. A. E. Mourant.

Specimens and transparencies to illustrate the geology of parts of the Plateau des Minquiers (Gulf of St. Malo).

Blezard, R. G.

The Upper Chalk and Danian in Denmark and Sweden.

Bottley, Mr. and Mrs. E. P.

(*a*) Exceptionally interesting Minerals and Fossils from the Varah and Puttrell Collections of Sheffield.

(*b*) New models of Prehistoric Animals.

(*c*) A New Collection of Crystal Models of proved success in teaching.

(*d*) The White Specific Gravity Balance. This second model is designed for instant and accurate reading to technical laboratories. It is a natural development from the field balance type we exhibited last year.

(*e*) Fine natural crystals.

Carreck, J. N.

The geology of the country between Chislehurst and Downe, Kent.

Carreck, Mrs. M. W.

(*a*) The Association's photograph albums with recent additions, including a new album.

(*b*) Geology teaching in a Comprehensive School.

Collins, J.

A selection of Post-Cretaceous decapod and cirripede Crustacea.

Cutrock Engineering Co. Ltd.

Ore polishing machine. Croft parallel grinder. 'Unicutta' rock cutting and grinding machine. Hammers. Chisels. Crystal models. Graticule slides. Goniometers. Stereometers. Cement (Lakeside). Augers. Clinometers. Dr. Dollar micrometer. Hotplate. Rock splitting and crushing machine.

Easton, Professor W. H.

Illustrations of Geological Features in the Western United States. Kodachrome colour slides.

Freere, R. H. (P. K. Dutt & Co. Ltd.)

Plastic display and collecting equipment. Geological hammers. Augers. Glassware. Hand tools. Slide cabinets. Magnifiers; lamps. Balance. Relief maps. Fluorescence apparatus. Specimen cabinet.

Guest, J. E.

Tertiary Basalts on NW. Iceland.

Gunner, A.

An Upper Chalk Flint.

Harrison, J. V. and E. A. Vincent

Colour slides of the Field Meeting in Brittany, September 1959.

Hart, J. McA.

Rocks from the East and Central Lizard.

Higginbottom, I. E. (George Wimpey & Co. Ltd., Central Laboratory)

The continuous stratification recorder. Photographs and diagrams illustrating the use of this equipment in marine geological surveys.

Kingston Technical College, Geology Section

Some Shropshire Fossils, Mendips Minerals and Rocks from Skye.

Leicester Museums and Art Gallery

Methods of Mounting Geological Material.

London Natural History Society

Selections from the Geology Section of the Centenary Exhibition of the London Natural History Society, 1958.

Marston, Alvan T.
Specimens of further interest relative to the Piltdown Discoveries.

Milbourne, R. A.
(*a*) Upper Cretaceous Cephalopods.
(*b*) Some interesting Gault Ammonites.

Owen, H. G.
Recent work on the Stratigraphy of the Lower Gault in the Weald.
(*a*) Fossils from the Lower Gault and Gault–Lower Greensand Junction of the Maidstone By-pass (East Section).
(*b*) The *cristatum* Subzone transgression in Kent.
(*c*) Stratigraphy of the *dentatus-spathi* Subzone.

Pitt, L. J., L. E. Holloway and F. H. Moore
A few specimens collected during the Field Meeting in Brittany, 1959.

Rast, N., F. J. Fitch and R. V. Beavon
The identification of ignimbrites in Wales.

Rhodes, J. E. W.
Photographs taken at the Weymouth Field Meeting, Whitsun 1959.

Stinton, Fred C.
Fossils collected at Sheppey during the Field Meeting on 2 May 1959.

Thomas, J. M. and J. E. Prentice
Carboniferous Goniatites from North Devon.

University of London Expedition to Jan Mayen Island, Greenland Sea, 1959
Photographs and specimens exhibited by J. Dollar, Leader; F. Fitch, Deputy Leader; J. Banfield; K. Brinsmead; P. Smith; R. Wright; D. Kinsman and B. Chadwick.

Venables, E. M.
Fossils from the London Clay of Bognor Regis.

Walker, George P. L.
(*a*) Conchoidal fracture of obsidian.
(*b*) Zeolites from giant amygdales.
(*c*) Compressional and tensional structures in rhyolite lavas.

Wright, C. W.
Recent acquisitions.

Wymer, J.
Palaeoliths from the Ancient Channel of the Thames at Henley.

THE LIBRARY

The Library Committee consisted of the President, Mrs. Ainsley, Messrs. L. R. Cox, O.B.E., N. B. Peake, M. K. Wells, J. W. Scott, Librarian of University College, London, and A. J. Smith (Librarian).

During the year a revision of the Exchange List was commenced. At present 49 Institutions in the British Isles and 107 Institutions in 35 overseas countries send copies of their publications to the Library in exchange for our PROCEEDINGS.

The following were added to the Exchange List in 1959:

Prace Muzeum Ziemi, from the Polish Geological Museum, Warsaw, Poland.

Science Abstracts of Earth Sciences, from the Institute of Scientific and Technical Information, Peking, China.

Fortschritte in der Geologie, from the Geological Society of North-Rhine and Westphalia, Germany.

Studii si cercetari de Geologie and *Revue de Géologie et Géographie*, from the Institute of Geology and Geography, Rumanian Academy, Bucharest, Rumania.

Bulletin of the Geological Survey, from the Geological Institute, Bogota, Colombia.

Records of the South Australian Museum, from the South Australian Museum, Adelaide, Australia.

Nouvelles Archives, from the Muséum des Sciences Naturelles, Lyons, France.

DONATIONS TO THE LIBRARY

ALLEN, P. 1959. The Wealden Environment: Anglo-Paris Basin. *Phil. Trans.* (b), **242,** 283–346.

ANDRUSOV, A. 1959. *Geologia Československých Karpǎt.* Czechoslovakian Academy of Geology.

BAER, A. 1959. *L'extrémité occidentale du Massif de l'Aar.* Thesis, Neuchatel.

BAKEWELL, R. 1833. *Geology.* London. Presented by F. Norris.

BALAKRISHNA, S. 1958. Velocity of Compressional Waves in some Indian Rocks. *Trans. Amer. geophys. Un.*, **39,** 711–12.

BIRCH, F. 1958. Differentiation of the Mantle. *Bull. geol. Soc. Amer.*, **69,** 483–6.

————. 1958. Interpretation of the Seismic Structure of the Crust. Reprint from *Contributions in Geophysics in honour of Beno Gutenberg.*

BLOOMFIELD, K. 1954. The Nachipere Series of Southern Nyasaland. *Trans. geol. Soc. S. Afr.*, **57,** 173–93.

————. 1958. The Chimwadzulu Hill Ultrabasic Body, Southern Nyasaland. *Trans. geol. Soc. S. Afr.*, **61,** 263–82.

————. 1959. The Geology of the Port Herald Area. *Nyasaland Geological Survey, Bulletin* 9. Zomba.

BROWN, P. E. 1957. An Occurrence of Soapstone in a Migmatitic Environment, Tanganyika. Reprinted from *Second Meeting, East-Central and Southern Regional Committee for Geology.* Tananarive. 177–82.

Bubleinikov, F. D. 1956. *Geologicheskie poiski v Rossii.* Moscow.

Burdon, D. J. 1959. *Handbook of the Geology of Jordan.* Government of the Hashemite Kingdom of Jordan.

Carreck, J. N. 1957. A Late Pleistocene Rodent and Amphibian Fauna from Levaton, South Devon. *Proc. Geol. Ass., Lond.*, **68,** 304–8.

Cherdynstev, V. V. 1956. *Rasprostranennost Kimicheskikh elementov.* Moscow.

Clark, S. P. 1957. Radiative Transfer in the Earth's Mantle. *Trans. Amer. geophys. Un.*, **38,** 931–8.

Cloke, P. L. 1958. Ore Genesis, the Source Bed Concept. *Econ. Geol.*, **53,** 493–6.

Coe, K. 1959. Boudinage Structure in West Cork, Ireland. *Geol. Mag.*, **96,** 191–200.

Cole, G. A. J. 1902. *Open Air Studies: An Introduction to Geology.* London. Presented by F. Norris.

Compton, R. R. 1958. Significance of Amphibole Paragenesis in the Bidwell Bar Region, California. *Amer. Min.*, **43,** 890-907.

Coope, G. R. 1959. A Late Pleistocene Insect Fauna from Chelford, Cheshire. *Proc. roy. Soc.* (B), **151,** 70–86.

Davis, A. G. & J. N. Carreck. 1958. Further Observations on a Quaternary Deposit at Bowleaze Cove. *Proc. Geol. Ass., Lond.*, **69,** 120–2.

Dearman, W. R. 1959. The Structure of the Culm Measures at Meldon, Devon. *Quart. J. geol. Soc. Lond.*, **115,** 65–106.

——— & N. E. Butcher. 1959. The Geology of the Devonian and Carboniferous Rocks of the North-West Border of the Dartmoor Granite. *Proc. Geol. Ass., Lond.*, **70,** 51–92.

Domarev, V. S. 1956. *Geologiya uranovykh mestorozhdenii kapitalisticheskikh stran.* Moscow.

Eagar, R. M. C. 1956. Naming Carboniferous Non-Marine Lamellibranchs. *Systematics Ass. Publ.*, No. 2, 111–16.

Forward, C. N. 1954. Ice Distribution in the Gulf of St. Lawrence. *Geographical Bulletin No. 6*, 45–84.

Gage, M. & R. P. Suggate. 1958. Glacial Chronology of the New Zealand Pleistocene. *Bull. geol. Soc. Amer.*, **69,** 589–98.

Garrels, R. M. 1957. Some Free Energy Values from Geologic Relations. *Amer. Min.*, **42,** 780–91.

Gee, E. R. 1958. Presidential Address to Geology, Geography and Anthropology section of 10th Pakistan Science Conference, Lahore.

Geological Survey of British Guiana. 1958. *Report on Antigua Conference 1955.* Demarara.

Geological Survey of Fiji. 1959. *Bulletin No. 1.* Suva, Fiji.

Geological Survey of Great Britain. 1958. *The Geology of the Country around Bridport and Yeovil.* London.

GEOLOGICAL SURVEY OF GREAT BRITAIN. 1958. *The Geology of the Midlothian Coalfield*. London.

————. 1959. *The Economic Geology of the Stirling and Clackmannan Coalfield*. London.

GEOLOGICAL SURVEY OF NYASALAND. 1959. *Report No. 2*. Zomba, Nyasaland.

GEOLOGICAL SURVEY OF SIERRA LEONE. 1958. *Report for year 1957*. Freetown.

GEOLOGICAL SURVEY OF SOMALILAND. 1959. Report on Geology of the Adadleh Area. *Mineral Resources Pamphlet No. 2*.

GEOLOGICAL SURVEY OF THE REPUBLIC OF SUDAN. 1958. *Bulletin No. 4*. Khartoum.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA. 1958. Gypsum Deposits of Western Australia. *Bulletin No. 6*. Department of Mines, Perth.

GEOLOGISTS' ASSOCIATION (JAMAICA GROUP). 1959. *Geonotes*, **1**.

GORSHKOV, G. P. 1957. *Obshchaya*. Moscow.

GREENSMITH, J. T. 1958. Preliminary Observations on Chemical Data from some British Upper Carboniferous Shales. *J. sediment. Petrol.*, **28**, 209–10.

————. 1958. The Introduction of Geology into the Secondary Modern School Curriculum. *Sch. Sci. Rev.*, **140**, 104–8.

HARPUM, J. R. 1957. Soapstone Bodies Produced by Magnesium Metasomatism in South-West Tanganyika. Reprinted from *Second Meeting, East-Central and Southern Regional Committee for Geology*. Tananarive. 183–92.

HOLLAND, C. H., J. D. LAWSON & V. G. WALMSLEY. 1959. A Revised Classification of the Ludlovian Succession at Ludlow. *Nature*, Lond., **184**, 1037–9.

HORNIBROOK, N. de B. 1958. New Zealand Upper Cretaceous and Tertiary Foraminiferal Zones and some Overseas Correlations. *Micropalaeontology*, **4**, 25–38.

HUTCHINSON, H. N. 1892. *Extinct Monsters*. London. Presented by F. Norris.

JAMES, T. C. & D. MCKIE. 1958. The Alteration of Pyrochlore to Columbite in Carbonatites in Tanganyika. *Min. Mag.*, **31**, 889–900.

KAYE, P. H. A. M. 1959. *Report on the Geology of the Leeward and British Virgin Islands*. St. Lucia.

KNOWLES, L. & F. A. MIDDLEMISS. 1958. The Lower Greensand in the Hindhead Area. *Proc. Geol. Ass., Lond.*, **69**, 105–238.

LEVITES, Y. M. 1956. *Istoricheskaya geologiya sosnovami paleontologii*. Moscow.

LYELL, C. 1833. *Principles of Geology*. Vol. 1. London. Presented by F. Norris.

McConnell, R. B. 1959. Fossils in the North Savannas and their Significance in the Search for Oil in British Guiana. Reprint from Royal Agricultural and Commercial Society's Journal *Timehri*, 1959.

Memoir of the Geological Survey. 1909. *The Geology of the South Wales Coalfield. Part X.* Presented by Hanley High School.

Middlemiss, F. A. 1958. Field Meeting in the Hindhead Area. *Proc. Geol. Ass., Lond.*, **69,** 239–43.

Nature Conservancy. 1958. *Report of the Nature Conservancy for 1958.* London.

————. 1959. *The Nature Conservancy: The First Ten Years.* London.

Nekhoroshev, V. P. 1958. *Geologiya Altaya. Geologicheskya Literatura U.S.S.R.* 1958. Moscow.

Pallister, J. W. 1959. Mineral Resources of Somaliland Protectorate. Reprinted from *Overseas Geology and Mineral Resources.* **7,** 154–65.

Playford, G. 1959. Permian Stratigraphy of the Wollaga Creek Area, Western Australia. *Journ. roy. Soc. W. Aust.*, **42,** 7–29.

Reeves, J. W. & J. F. Kirkaldy. 1958. Field Meetings in the Cretaceous of the Western Part of Weald. *Proc. Geol. Ass., Lond.*, **69,** 262–7.

Ringwood, A. E. 1958. The Constitution of the Mantle. II. *Geochim. et cosmoch. Acta*, **15,** 18–29.

————. 1958. The Constitution of the Mantle. III. *Geochim. et cosmoch. Acta*, **15,** 195–212.

————. 1959. On the Chemical Evolution of the Planets. *Geochim. et cosmoch. Acta*, **15,** 257–83.

Sampson, D. N. 1957. A Brief Comparison between the Mica-bearing Pegmatites of the Uluguru Mountains and the Morogoro District, Tanganyika. Reprinted from *Second Meeting, East-Central and Southern Regional Committees for Geology*. Tananarive. 139–56.

Schmalz, R. F. 1959. A Note on the System Fe_2O_3–H_2O. *J. geophys. Res.*, **64,** 575–9.

Service Geologique du Congo Belge. 1958. La Carbonatite Lueshe (Kivu) par A. Meyer. *Bulletin 8.*

Shillitoe, J. S. 1958. Report on Tests carried out on Woolwich and Reading Strata during Site Investigation. Parts I and II. *Brit. Engr*, **19,** 105–10 and 148–57.

Shotton, F. W. 1959. Insects in Pleistocene Deposits. Reprint from *Journ. Inst. Biol.*, **6,** 63–5.

———— & I. Strachan. 1959. The Investigation of a Peat Moor at Rodbaston, Staffordshire. *Quart. J. geol. Soc. Lond.*, **115,** 1–16.

Steiner, A. 1958. Occurrence of Wairakite at the Geysers, California. *Amer. Min.*, **43,** 781–84.

Strachan, I. 1959. Graptolites from the *Ludibundus* Beds of Tränen, Sweden. *Bull. geol. Instn Univ. Upsala*, **38,** 47–68.

THOMPSON, G. A. & C. H. SANDBERG. 1958. Structural Significance of Gravity Surveys in the Virginia City–Mount Rose Area. *Bull. geol. Soc. Amer.*, **69**, 1269–82.

VOLODINKO, K. G. 1957. *Kolonkovoe burenie*. Moscow.

WHITTEN, E. H. T. 1959. A Study of Two Directions of Folding. *J. Geol.*, **67**, 14–47.

———. 1959. Tuffisites and Magnetite Tuffisites from Tory Island, Ireland. *Amer. J. Sci.*, **257**, 113–37.

———. 1959. Composition Trends in a Granite: Modal Variation and Ghost Stratigraphy in Part of the Donegal Granite, Eire. *J. geophys. Res.*, **64**, 835–48.

WILLIAMSON, I. A. 1959. The Skeleron or York and Lancaster Lead Mines. Reprinted from *Journal of the Past and Present Mining Students' Association*, **1**, 46–50.

WILLS, L. J. 1959. External Anatomy of some Carboniferous 'Scorpions'. Part. I. *Palaeontology*, **1**, 261–82.

OBITUARY NOTICES, 1960

EDMUND ERNEST STOCKWELL BROWN, to whom the Association is greatly indebted, died, after a short but painful illness, on 13 September 1959, at his home in Sidcup.

Brown was born at Lewisham on 21 October 1892. Educated at elementary schools and by private tuition, Brown entered the Secretary's office of the General Post Office as a boy clerk in 1908. He remained in the Post Office for the next thirty-four years and in 1941 was awarded the M.B.E. In 1942 Brown was transferred to the Ministry of Supply on his appointment as Head of a Mission sent to Brazil to purchase minerals of strategic importance, especially quartz of quality suitable for piezo-electric purposes. He was based at Rio de Janeiro, but the work involved a considerable amount of travelling both in Brazil and also in the United States and Canada. On his return to England in 1946, Brown was appointed to the Ministry of Civil Aviation and remained there as a Senior Executive Officer until his retirement in January 1953

When he was about fifteen, Brown became interested in the geology of his home area. He began to collect fossils and to read geological books. In 1913 he joined the Association and in 1922 was elected to Council. For the next thirty-one years, apart from the interruption of the war, Brown continued to serve on Council, first as an Ordinary Member (1922–5), then as General Secretary (1925–37), as Vice-President from 1937–9, 1946–7 and 1950–3, and as President from 1948–50. After his retirement from Council, Brown continued to serve the Association both as an 'elder statesman' and also, from 1954–8, as a most keenly interested member of the Centenary Committee. He joined the Geological Society in 1922 and served on the Council of that body from 1939–43.

Brown's twelve-year period of service as General Secretary is the longest in the history of the Association. It was by no means an easy period, for Brown was in office during what he used to refer to as 'the troubles'—the final stages of the long-drawn-out controversy between two rival schools of thought as regards the purpose of the Association (see Centenary *History*, pp. 11–12). That was not all, for much extra work was caused by the litigation, eventually successful, for treating the Association as a charitable body with exemption for Income Tax (Centenary *History*, pp. 12–14). Brown was an extremely active and efficient Secretary. His successor, Mr. A. G. Bell, writes: 'I was struck when I took over by the orderly and methodical way in which all records were kept. I found most useful a diary showing when the various matters should be attended to throughout the year, and all in good time to avoid last-minute correspondence. . . . In Brown's time the addressing and stock-keeping were done by a private individual employed by him and he was responsible for sales of back numbers and pamphlets, now done by Benham's. . . . I have tried to estimate the total time required by the Secretary and make it rather less than an hour a day all the year round. I was retired and usually worked from 10–12 in the mornings, but Brown was in harness and must have spent much of his evenings and Sundays over the work.' In the never-ceasing paper-work Brown received much help from his wife and daughter.

Brown interpreted the duties of Secretary as involving much more than meticulously precise 'paper-work'. The success and well-being of the Association meant very much to him and he was careful to keep his finger on the Association's pulse. At Field Meetings and Annual Reunions he was always enlarging his personal acquaintanceship of the members—in particular he made a point of welcoming new members. Mr. and Mrs. Brown, often accompanied by their daughter Molly, were amongst the most regular of attenders at Field Meetings, especially at the longer Field Meetings. During the day Brown took a very keen interest in the geology and his name has several times received honourable mention in the reports (e.g. for the discovery of a new fossiliferous locality near St. Davids, South Wales (*Proc. Geol. Ass., Lond.*, 1930, **41**, 426). In the evenings, Mr. and Mrs. Brown soon became the centre of a convivial party. On 26 February 1937 the Council, together with past-Presidents, entertained Mr. and Mrs. Brown to a dinner at Stewart's Restaurant, Piccadilly, in recognition of his twelve years' service as General Secretary. Thirty-eight were present at an occasion which is unique in the Association's annals. Brown's great services to the Association were stressed at the Annual General Meetings in 1941 and 1946. At the first he received the Foulerton Award, at the second he was elected to Honorary Membership. It was very fitting that in 1946, Honorary Membership was also conferred on the late Dr. A. J. Bull and Mr. G. S. Sweeting, who had worked with Brown for many years as fellow officers.

Brown's deep knowledge of the Association was a great asset when he occupied the Presidential Chair. His adept handling of Council Meetings is referred to on p. 123 of the Centenary *History*. His two Presidential Addresses make very interesting reading. The first, 'Work for Amateur Geologists' (1949), is the product of his long experience and is full of good sense and helpful advice. It covers the whole cycle of a geologist, from the first interest in the subject to the final stage of thinking how best to dispose of a private collection. During his retirement Brown acted on what he had written in 1949. He worked systematically through his extensive, varied and fully labelled collection. The choicest specimens were distributed amongst the appropriate specialists. The bulk of the remainder was offered to, and gratefully accepted by, various Geological Departments, including those of the Universities of Liverpool and Southampton and Queen Mary College, University of London. His second Presidential Address (1950), based on his war-time activities, dealt with quartz crystals, especially those of Brazil. Those who heard this address will recall that it was illustrated by many fine specimens and also by carefully chosen lantern-slides, some of which made the required point in an unusual, but distinctly effective, manner.

On the Contents page of the Centenary *History*, Brown's name appears as the writer of two chapters, 'General Meetings' and 'The Officers', both topics with which he was particularly fitted to deal. He also took a very practical interest in other sections of the *History*. He helped to select, mainly from the Association's albums, the illustrations, but he was naturally overruled when he suggested that his own portrait should not appear. It was very appropriate that the portrait which he rather reluctantly offered must clearly have been taken during a Field Meeting.

So far, and very naturally, Brown's administrative work has been stressed. But he was also a good field geologist, thoroughly familiar with the Lower Tertiary beds of south-east London. He collaborated with S. Priest in describing temporary sections in Watling Street (*Proc. Geol. Ass., Lond.*, 1924), with A. Wrigley in the Sidcup By-Pass (*ibid*, 1925) and with F. H. Edmunds with describing and discussing the origin of an Unusual 'Pipe' in the Blackheath Beds at Bromley Hill (*ibid*, 1929). He led Field Meetings to Ruxley and Crays (1921), and to the Watling Street sections (1923). Further afield he contributed to the account of the Canterbury District (*ibid*, 1925) and led Field Meetings to Herne Bay and Reculvers in 1925 and 1936. Brown was also a founder member of the Weald Research Committee and was allocated the area around Borough Green and Wateringbury in Kent. He led Field Meetings to this area in 1928, 1937 and, with Dr. G. W. Himus, in 1938. In 1939 he described a Tufaceous Deposit at West Malling, A. S. Kennard adding an appendix on the non-marine Mollusca, and in 1941 he published a valuable account of the Folkestone Sands and basal beds of the Gault in his area.

Many of the older members will have kindly memories of Ernest Brown. To the younger members he was, perhaps, not so well known; but they too should remember that the present success of the Association is due in no small measure to Brown's many years of devoted service.

J. F. K.

JOSEPH FOWLER, whose death occurred at Freshford, near Bath, on 19 December 1958, at the age of eighty-six, will be particularly remembered for his researches into the geology and history of Sherborne, Dorset, carried out during the years of his retirement. Born at Wakefield, Yorkshire, he graduated at the University of Durham, entered the Church, and for a number of years was Vicar of Milton, Portsmouth. A love of teaching led him to resign his living in order to found a preparatory school for boys at

Avisford, near Arundel, Sussex. He retired from its headship in 1934 and settled in Sherborne.

A keen interest in archaeology and geology had already led to the publication of papers on 'Palaeoliths found at Slindon' (*Sussex Archaeol. Coll.*, **70**, 197–200, 1929) and 'The one hundred feet raised beach between Arundel and Chichester' (*Quart. J. geol. Soc.*, **88**, 84–99, 1932). Remarkably active until a very advanced age, he pursued his researches into the past at Sherborne with unabated enthusiasm, no geological section, temporary or otherwise, within walking or cycling distance of his home escaping his attention. His work *Sherborne Behind the Seen* appeared in 1936, his *Stones of Sherborne Abbey* in 1938, and his last paper, 'The Geology of the Thornford Pipe-Trench' (*Proc. Dorset nat. Hist. Fld Cl.*, **78**, 51–7), in 1957. His most important work, *Mediaeval Sherborne*, the outcome of years of research into ancient records, appeared in 1951.

Fowler joined the Geologists' Association in 1910 and acted as Field Secretary for the Whitsun Field Meeting based on Yeovil in May 1939. Probably his last personal contact with the Association was during the Whitsun Field Meeting in the Shaftesbury district in 1954, when he joined the party one day. He was tall, thin, bespectacled and serious but kindly, with a mien that disclosed his earlier vocation. Geologists who visited Sherborne were assured of a hospitable welcome at his home, and it was his joy to encourage the younger generation to study rocks in the field and collect fossils.

L.R.C.

JOHN WELLER SANDFORD FAWCETT died suddenly on 4 January 1960 at the age of fifty-nine.

Educated at Radley College, he started life as a chemist. Later, he trained as a civil engineer and, at the time of his death, was senior partner of Sandford Fawcett and Partners, consulting engineers of Westminster, specialising in the design of water-works, sewage and sewage treatment schemes. Most of Fawcett's geological work was, therefore, confined to engineering problems. He was a keen observer and published brief notes on sections of interest encountered during his work on the Colne Valley Sewerage Board scheme. He joined the Association in 1946.

He was known to members of the Association mainly through his participation in the longer field meetings.

S.W.H.

WILLIAM DAVID WARE was born at Ystradgynlais, Breconshire, on 25 July 1894. Although he lived his whole life there, apart from service on the Western Front in the First World War, he won a reputation for his geological researches which extended beyond this country. He became a member of the Association in 1926.

His ability was shown early when he gained a scholarship to Brecon; but separation from his family, even for five days a week, was too much for the boy, and he returned home. After leaving school, the rest of his life, except for a few short periods, was spent in the coal-mines.

A small incident in World War I, while he was guarding German prisoners of war digging wells, turned Ware's lively mind to geology. One of them picked up from the Chalk something which he pocketed. Ware investigated and was shown an echinoid, and he decided, in order to help relieve the boredom, to look out for further fossils thrown up by the diggings, though at that time he knew nothing about them. In this way his appetite was whetted.

Returning to South Wales on demobilisation, Ware, quite unguided and with none of the usual scientific contacts, began to teach himself geology, by reading such books as he could acquire or borrow, and by observing geological phenomena both in the mine and in his trampings over the Welsh countryside—he even laboriously ground his own thin rock-sections. Thus by keen observation and his own experience, he became familiar with the succession of floral and faunal assemblages in the local Upper Carboniferous and their relationship to the various coal-seams. He received no encouragement from the pit authorities at first, however, and it was only when his proffered advice, sceptically received initially, was triumphantly proved correct during the sinking of the Cefn Coed borings that Ware's worth was locally appreciated. Collecting from the horizons penetrated, he was able to identify the seams met with by comparing the fossils he obtained and their succession with those of the Cwmgorse borehole already described by Dr. Emily Dix and Professor (later Sir) Arthur Trueman. Further, he recognised and named the richly fossiliferous Cefn Coed Marine Bed. His paper, 'An Account of the Geology of the Cefn Coed Sinkings', was published in the *Proc. S. Wales Inst. Engineers*, **46,** 1930.

It was during the course of these investigations that Ware met Professor Trueman, who immediately saw his potentialities and thereafter encouraged and helped him in every way. In 1932 they published a joint paper on 'Additions to the Fauna of the Coal Measures of South Wales', *Proc. S. Wales Inst. Engineers*, **48.** Ware also turned his attention to the Millstone Grit of South Wales, especially of Carmarthenshire, and the importance of his work was recognised by the award to him of a grant from the Levenhulme Fund for the furtherance of his researches in this field. The results were published in our own PROCEEDINGS in 1939. A little later he published, with Dr. Dix, on 'The Occurrence of the Similis–Pulchra Zone in the Pembrokeshire Coalfield', *Advancement of Science*, **1** (2), 1940. Ware received the Foulerton Award from our Association in 1945, and the Lyell Fund from the Geological Society in 1948.

Ware did not publish much, but his knowledge was freely at the command of any who were interested in Upper Carboniferous stratigraphy and palaeontology. It was based on an intimate acquaintance with rocks and fossils both below and above ground. No plant fragment was too small for examination, and the significance of slight differences, too subtle to be noticed and appreciated by those not as familiar as he with the succession of Carboniferous floras in the field, was readily observed.

Despite his detailed knowledge, Ware was always kindly in his just criticism of others, and he tempered it with a gentle humour. Diffidence and modesty were two of the outstanding characteristics of this broad-shouldered, fair-haired miner. But the steady gaze of his blue eyes, as he fluently discussed Carboniferous geology with a soft-spoken authority, proclaimed that in his search for truth he knew no false inhibitions.

Ware retired from the mines in March 1959, bent on monographing the Pecopterids of South Wales, but he was already unknowingly stricken with the malady from which he died some seven months later on 28 October. His wife, son and daughter survive him.

H.D.T.

COLIN BLAIR WILSON was born on 24 June 1928 and was orphaned while still a child. He came up to Emmanuel College, Cambridge, in 1949 and read for the Natural Sciences Tripos taking Part II in Geology in 1952. In that year he joined his first Spitsbergen expedition and was introduced to the Hecla Hoek rocks on which he worked till his death. He returned with the Cambridge Spitsbergen Expedition 1953 and then on his own initiative he organised a series of remarkable journeys to elucidate further the structure and stratigraphy of these rocks. In 1955 with D. Masson Smith he visited Ny Friesland from a base in Billefjorden, making long solo sledge journeys. Beginning in the same company in 1956 Ny Friesland was visited by small boat from the North and he continued alone with sledge and finally by small boat round the exposed NW. coasts of Spitsbergen from Wijdefjorden to Longyearbyen. In 1957 journeying solo both ways by sea he completed his survey of Middle and Upper Hecla Hoek Rocks by sledge and in 1958 having perfected this technique he worked alone by boat and sledge in Oscar II Land. While in the midst of active preparations to continue this work in company with a large expedition in 1959 he met with a fatal accident at his home in Cambridge during May 1959.

It was only latterly that Wilson was persuaded of the value of publishing his results and, after a preliminary joint survey of the whole field published in 1956, in 1958 the first detailed paper appeared on the Lower Middle Hecla Hoek Rocks in the *Geological Magazine*. Happily a manuscript on the Upper Middle Hecla Hoek Rocks is in an advanced state of preparation and he was already collaborating on the higher rocks the results of which are being prepared for publication. Viewed as a whole this is no mean achievement, but Wilson was not driven by any ordinary ambition. In the service of his own insatiable curiosity he employed intellectual gifts of a high order and quite extraordinary physical courage and prowess. But he was innocent of wordly values preferring to keep his achievements private.

Wilson had sufficient private means to be independent of the ordinary routine and conventions. He was generous yet lived simply himself. He enjoyed music, read widely, loved wild and remote country, and won the affection of his friends, but he was first and foremost an investigator. He became a Life Member of the Association in 1951.

W.B.H.

A CENTENARY LECTURE

The Pleistocene Succession in the London Basin

by S. W. WOOLDRIDGE

Read 10 October 1958

WHEN I RECEIVED the Council's invitation to deliver this lecture, I had little difficulty or hesitation in choosing a subject. Professor Read has recorded how, in similar case, he sought a topic marking a convergence between his own chief interests and those of the Association. No such problem confronted me. My first chief scientific interest was in the drift-geology or, more generally, the post-Eocene history of the London area, and friends in this Association, too many of them now gone before, provided a large part of my Geological education. The first meeting that I attended following my election in 1917 was Mr. George Barrow's Presidential Address in 1918: at my then early age and three years before graduation I was already deeply engrossed in the problems of the older or high-level drifts of the area. I had made the acquaintance of Dr. A. E. Salter and followed out on the ground many of his own observations. As a student in training I could not but be aware of the prevailing Palaeozoic and igneous squint of British Geology and the small regard in which Tertiary and Pleistocene investigations were commonly held. Nevertheless, I was by conviction and choice a soft-rock geologist, believing in the virtue of doing the job that was nearest. Or, in the more exalted Biblical language, believing, as I still do, that 'wisdom is before him that hath understanding but the eyes of the fool are in the ends of the Earth'; or, at any rate, in what have recently been termed 'the Atlantic ends of Europe'. There was in any case no doubt where a major concern of the Association lay in the days of our 'Gravels' and 'Temporary Sections' committees.

None the less, if the choice of a subject gave me little trouble, the subject itself is vast, a little unwieldy and highly disputable. It would occupy the whole of my time this evening merely to recite a list of the communications, including Field Meeting reports, which have contributed to our subject. A prevailing disease of the subject has always been a sort of parochial myopia. Whatever this pit west of Brentwood (say) may seem to show, someone has seen a now invisible trench east of Brentwood where his own eyes, as he solemnly assures you, have perceived something entirely different.

This leads me to take occasion to express our sense of the indispensable value of the work of the Geological Survey. The decade which saw our foundation coincided with the last stages of the drift survey of the London area, and although innumerable individual and amateur observers have contributed much of our knowledge, it would have been singularly discontinuous and incoherent without the faithful and consistent scrutiny of the whole of the ground maintained by the Survey Officers. A unitary London District geological map, with drift, first appeared in 1874 and Whitaker's 1889 Memoir contained the first systematic account of the drifts. Since then we have been deeply indebted to the six-inch re-survey begun about 1910 and preceded by the special survey of the Thames Valley drifts by Howe and Pocock in the early years of the century. It is particularly as an interim progress report on the six-inch re-survey that Barrow's address (1919) is so signal and germinal a contribution. Though described by one of his great successors in Highland geology as 'brilliant but uncertain', I found in my association with him, thirty years ago, abundant evidence of the brilliance, but not of the uncertainty. In my experience Barrow was very rarely in error in either observation or judgment though occasionally he was right for the wrong reasons. A great deal of the work I have myself attempted arose directly out of suggestions he had made. Everything that he wrote in his London period is worthy of close study and attention and I cannot let the occasion pass without recording my own indebtedness to him. I was interested to discover that he was educated at my own College in contrast to both Prestwich and Whitaker who attended 'the other place', near the back rather than the front of the Taplow Terrace.

Although the customary picture of the London Basin, on small-scale geological maps, shows only the major downfold floored by Eocene rocks, in actual fact half or more of the surface is underlain by Pleistocene accumulations. Everywhere from the high Chalk rims at or above 750 feet O.D. to the floor of the Thames Valley, locally below sea-level, we shall find ourselves standing on or near a gravel-flat, or a sheet of stony clay, both of them locally covered or replaced by stoneless loams (Fig. 1). In all, there are some fifteen mappably distinct formations. It is rare for any pair of them to be unarguably superimposed and nowhere is there an orderly stratified succession. The disjunct sheets or masses rest unconformably on the Chalk and Eocene rocks. They are almost exclusively continental deposits, accumulated on the land-surface, hence the natural development of a physiographic approach to their problems. Even for the rudimentary step of ranging them in order, palaeontology fails us or, at best, is only locally either applicable or coherent. They can in fact be ranged in order only by reference to their elevation and constitution. The accepted presupposition of London drift geology for the last century, i.e. since the days of Prestwich, is that higher level deposits are older than those of lower level. This implies the conclusion, unwelcome to some, that throughout the greater part of our region differential warping has been in abeyance during

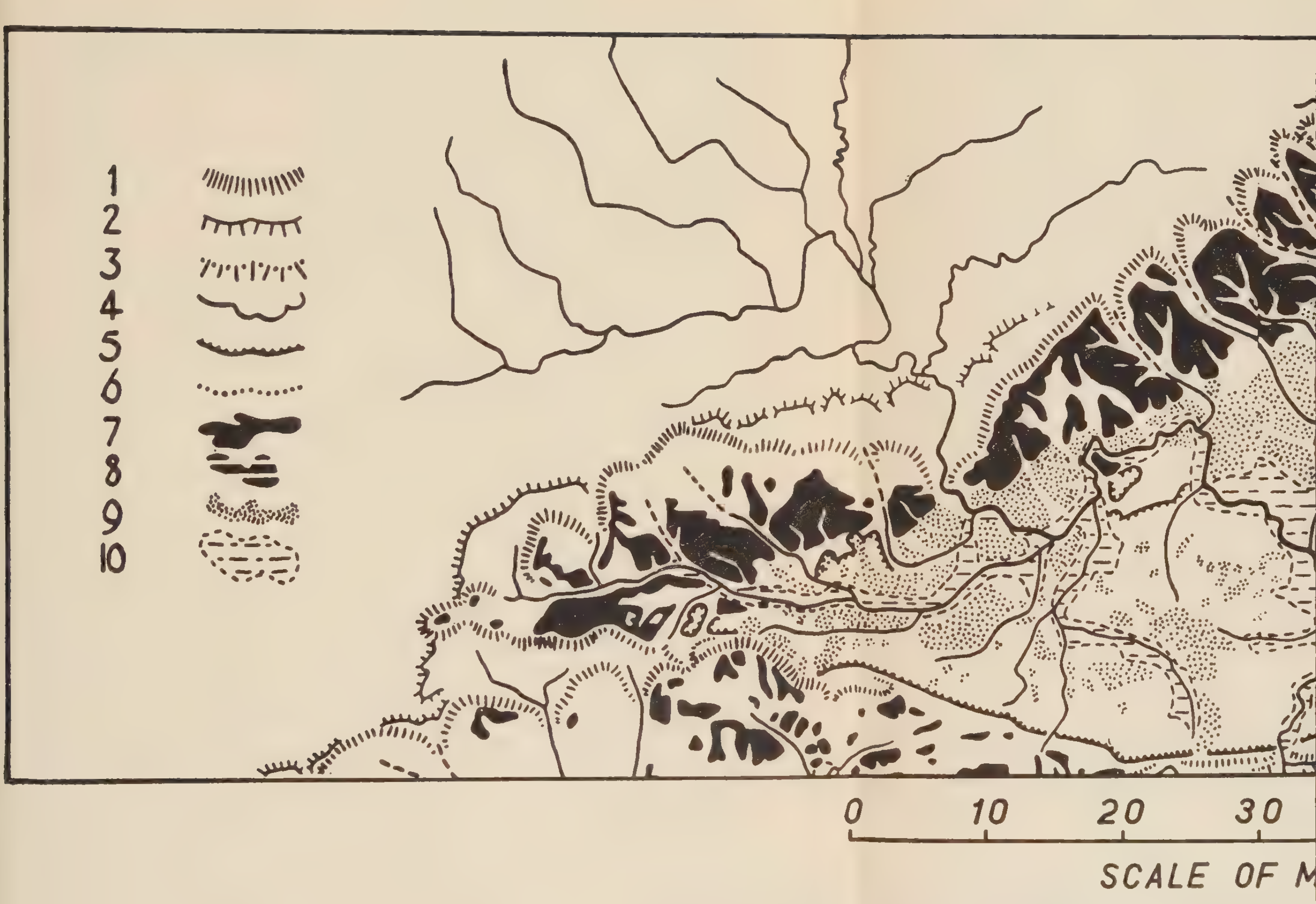
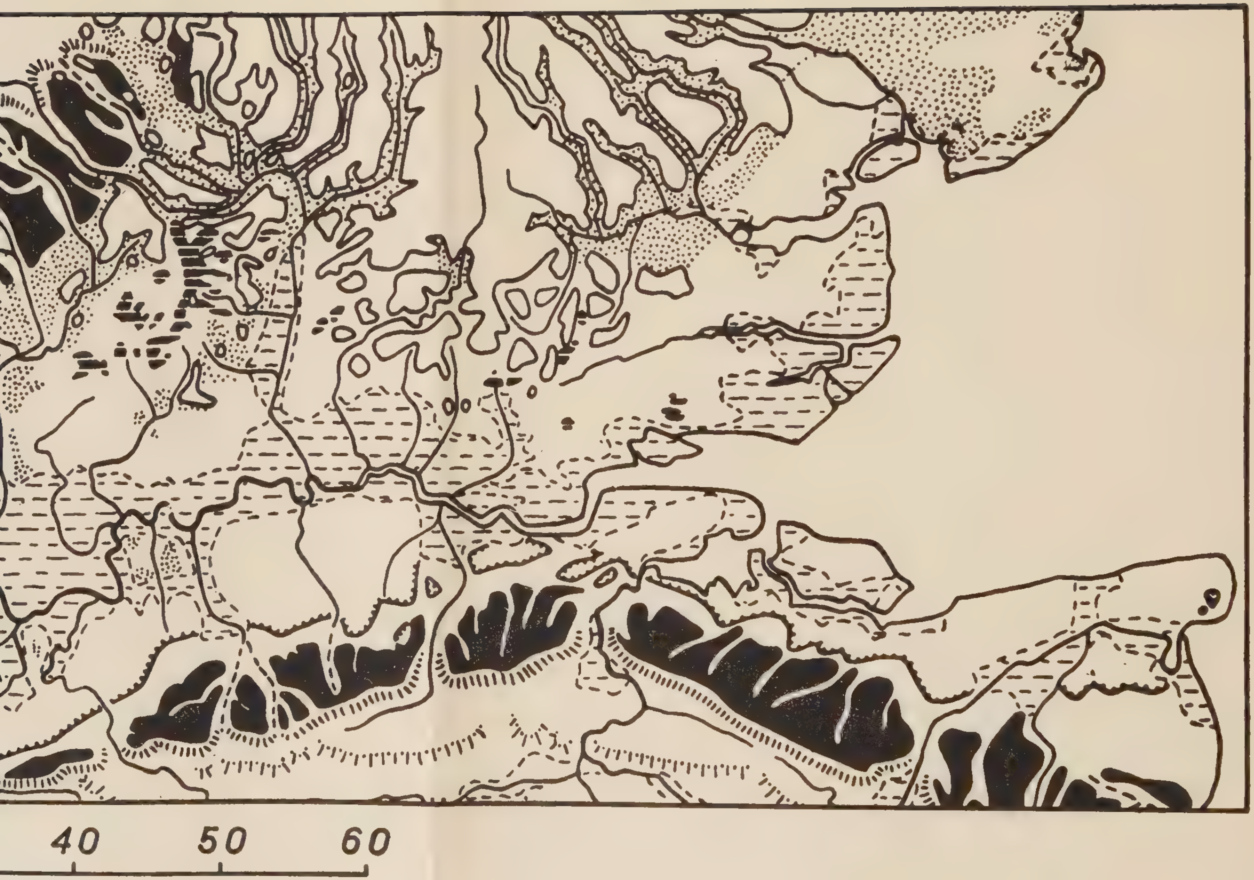


Fig. 1. Some fundamental features in the physiography of South-East England. 1
sand escarpment. 4. Boundary of the Boulder Clay outcrop. 5. Boundary of th
(not shown). 7. Plateau drifts of the Chalk uplands. 8. Plateau gravels of Stage I.



Chalk escarpment. 2. Malmstone escarpment. 3. Lower Green- e Eocene outcrop. 6. Boundary of the Hastings Sands outcrop 9. Plateau gravels of Stage II. 10. Terrace gravels and alluvium

[*To face p.* 114

Pleistocene times—say during the last million years. I am not forgetting the recent authoritative reminder from the Chair of the Geological Society of Lyell's dictum that 'the energy of the subterranean movements has always been uniform as regards the whole Earth'. But the extreme uniformitarian corollary that earth-movement, like denudation, is unceasing requires important reservations. Earth-movement is no doubt always in progress somewhere, but not everywhere! We have no doubt been prone to regard orogenesis as too narrowly localised in time, but it is certainly and significantly localised in space. We may accept the evidence of the New World that the Cascadian Revolution culminated in the Middle Pleistocene and that similar late movements are evidenced in South America and the Himalayas, but it has demonstrably not complicated our own region. To those who occasionally seek to invoke it here, as a species of tectonic niblick, to get them out of 'bad lies', I would reply that it takes more than isolated 'push-moraine' features in mid-Essex, or kindred disturbances south of Royston, to justify the preposterous hypothesis of irregular upheaval and depression over the 3000-odd square miles of the London Basin. I remain firmly convinced that no such movements have taken place. For those of us who hold that view, it is, please note, not an assumption but, as we feel, a demonstrated fact. What is true is that during the evolution of our South-Eastern landscape there has been an **over-all drop of sea-level** superimposed upon and independent of the admitted glacial oscillation of sea-level. Zeuner (1945) estimates that such general depression has amounted to some seventy metres (*c.* 230 feet) during the last 600,000 years, i.e. about one-tenth of a millimetre annually. Even if one questions the Milankovitch radiation dates used in his computation, his conclusion is evidently of the right order, since the water equivalent of the existing ice masses (50 m.) if returned to the ocean would leave the Sicilian shore-line about fifty metres above the restored sea-level.

In the light of this fact, which rests on a world rather than a local basis, I shall adopt a frankly altitudinal approach to our problem and group the deposits in three main stages, **I, II** and **III,** based essentially upon elevation. (This is the broad grouping used by Prof. D. L. Linton and myself in our monograph 'Structure, Surface and Drainage in SE. England' (1955).)

The Stage **I** deposits are, broadly, the summit deposits, of the hill-tops and high plateaux. The Stage **II** deposits, broadly those styled 'glacial' on the Survey maps, are dominantly but not exclusively Plateau deposits, locally they are valley deposits. The Stage **III** deposits comprise the acknowledged valley or terrace drifts. This broad grouping is not some peculiar and heretical invention of my own. It is clearly implicit in Whitaker's 1889 Memoir, in Prestwich's great paper of the following year and in the work of A. E. Salter and Barrow.

With declining elevation the successive 'psephitic' deposits show increasing complexity of constitution. The general picture is singularly simple and comprehensible, as material from near or beyond the borders of the region is successively dumped in the Eocene basin or the Thames Valley. Barrow's classification was into *Local, Neighbouring, and Far-travelled, constituents.* In a word the higher and older deposits are 'oligomict', but increasingly 'polymict' as we descend into later stages. The record was complicated at least twice by the influx of glacially-borne erratics. We have evidence that the Chalk was breached and the Lower Greensand laid under contribution during Eocene times, but no large influx of lower Cretaceous debris appears until late in our Stage **I.** Stage **II** witnesses the arrival of Bunter debris in force, though I suspect that the forerunners of the later host of Bunter quartzites appeared in Stage **I.** Jurassic debris, by virtue of its limited durability, is rare except where glacially transported, but it is not unknown.

In considering, first, the Stage I deposits we must include some reference to the superficial deposits of the high Chalk margins of the Basin. Here we have first to reckon with the Clay-with-Flints and its associated materials. It seems probable that the true Clay-with-Flints is, as Codrington and Whitaker supposed, a residue of dissolution of the Chalk. Jukes-Browne in 1906 indicated some of the difficulties of this hypothesis. His plea for the attribution of an Eocene quota to the deposit is unarguably reasonable and acceptable, but his own theory went further than this and regarded many of the Clay-with-Flints masses of Hants as little more than rough 'pseudomorphs' of Eocene outliers. This may be true in parts of Hampshire. It is quite untrue on the margins of the London Basin. Here the Chalk country shows three distinct morphological elements: (a) the highest or summit areas, above 700 feet, (b) the broad flat, bearing remains of marine deposits of the Netley Heath type, and (c) the true dip-slope or sub-Eocene surface stripped of its Tertiary over-burden. On the first of these surfaces a true residual Clay-with-Flints certainly occurs, but it is conspicuously absent from the third. These facts are evidently consistent with the 'Chalk-residue theory', since the high summit areas are relics of the general mid-Tertiary or Mio-Pliocene peneplain; it would be surprising if the long exposure of this surface had left no traces of contemporary or reworked regolith. By contrast, the sub-Eocene surface has seen the light of day only during Pleistocene times. It is probable that X-ray analysis of the clay-fraction of these deposits will throw much further light on their nature and origin. Meanwhile it is well to remember that the ancient regolith referred to above, accumulated in a climate differing widely from that of the present. An undisturbed soil-profile on the peneplain surface might be expected to show almost lateritic characters and signs of such have occasionally been noted by pedologists.

The second theory of the Clay-with-Flints is the 'glacial origin', proposed by Sherlock & Noble (1912). This had on the whole an undeservedly chilly reception, on the grounds that what these authors described 'was not really Clay-with-Flints' and that while the invocation of an ice-sheet on the Chiltern Hills was perhaps remotely possible, no such hypothesis could avail for the similar deposits of the North Downs. None the less, Dewey wrote in the Dartford Memoir of the deposits of the latter area that 'they frequently show the effects of movement especially when in contact with Tertiary outliers; they undercut the slopes of the outliers and divide into streams which sweep round obstacles and re-unite'. Both here and in the Chilterns indeed, the deposits show some of the features of a till, and since, as we shall see, there are other grounds for invoking an early ice-sheet, at least on the Chilterns, we can legitimately keep an open mind on the 'glacial theory'. The recent study by Morley Davies (1953) of the distribution of 'Sarsens' in the area is also consistent with these ideas.

Concerning the associated 'plateau-brickearths' no dissent is in view from Barrow's conclusion, i.e. that the deposits mark the long-period filling of major solution hollows. To such filling I suspect that loessic or windblown material made a contribution.

It is of high interest that the work of the Soil Survey on the Aylesbury Sheet is now complete. In their terminology, our Clay-with-Flints is the Winchester Series while much of the plateau-brickearth falls in their Batcombe Series. It will be very instructive to compare the results of Drift and Soil survey in this area.

The most important element in our Stage I is certainly provided by the high-level marine deposits formerly regarded as Pliocene but now following the re-definition of the Pleistocene base to be assigned to the early Pleistocene. I entertain little doubt that the deposits are in fact the representative of the Calabrian stage of the Mediterranean, as earlier suggested by Zeuner. When the remarkably consistent petrographic characters and physiographic relations of the deposits were first recognised, the only fauna with which they could be plausibly associated was that of the Lenham Beds. The Red Crag faunas at Netley Heath and Rothamsted changed the position, but also seem to call for a careful re-examination of the Lenham fauna, many of whose elements clearly range up into the Red Crag. As things stand at present there are two possibilities. It is probable that all the deposits are, in fact, of Waltonian (Calabrian) age. Alternatively, it is possible that just as the 'Pliocene' sea retreated northwards, disposing its deposits in their characteristic, if puzzling, relation of 'imbricate off-lap', so earlier it advanced southwards and westwards, so that the deposits are older in Kent than in Surrey or Herts. It must be left to the palaeontologists to resolve the matter. My own sojourn with the recent East Anglian excursion has considerably shaken my faith in dating by molluscan faunas and I shall not burn my fingers and reveal my own ignorance by dabbling in troubled waters in which 'progress (?)' seems only to make confusion worse confounded.

What perhaps may be fitly and fairly emphasised is that the importance of the physical episode of what I shall call outright, 'the Calabrian transgression', stands unaffected by wavering opinion as to its precise date. The wave-cut platform as well seen on and around Chussex Plain on the North Downs, is on any standard an impressive feature and I may recall that this '600-foot Sea' is widely reported in other parts of Britain. Its upper limit is the latter-day 'high water mark' of south-east England. The emergence of this sea-floor was 'when Britain *last* at Heaven's command arose above the azure main' and its widely preserved remnants mark the natural summit plane of our region. It has been 'uplifted' in the London area without appreciable warping, or much more probably, as I feel, been left high and dry by cumulative negative eustatic shifts of sea-level. Nevertheless, when we recall the situation of the Red Crag at (say) Walton-on-the-Naze, we are left in no doubt that the sub-Calabrian surface is warped down unmistakably towards the North Sea depression, somewhere in Essex.

It is a complication of our problem that we have another and later group of summit deposits in the area, the Pebble Gravel of the Geological Survey. Following Barrow I concluded in 1927 that these deposits were later though not much later than those now classed as Calabrian. The first clear recognition of the deposits and their relation was by McKenny Hughes (1868). Twenty-two years later came Prestwich's 'Westleton paper' (1890) correlating the Pebble Gravel with his Westleton Beds in East Anglia. I am satisfied that this correlation is essentially correct, but space will not avail me to trace the history of the subsequent 'boggling' and confusion. I must not, however, ignore the fact that Dr. Solomon (1935) gave a new and widened definition of the Westleton Beds which is, to me, quite unacceptable. I cannot believe that it is proper or permissible to concentrate on the microscopic grains of a gravelly deposit, ignoring or underrating the importance of its larger macroscopic constituents. Having worked a long apprenticeship in 'heavy-mineral' work, I am not joining any chorus of general scepticism such as has sometimes been offered to the results of such work. I claim only that macroscopic and microscopic components are at least of equal importance. The association in the Pebble Gravel of rounded flint pebbles with small white quartz pebbles is completely unmistakable, a unique collocation of pebbly constituents. Moreover, its associated mineral suite is highly consistent. It was of great importance that Dr. Solomon recognised this suite in the Westleton Beds and still more important the local admixture of material from the North Sea Drift. It is perfectly true that some of the Stage II or glacial gravels also yield a limited or impoverished mineral suite, but it appears to me the height of flagrant unreason to ignore in these latter enormous Bunter Quartzites a little rolled flints which indicate a different origin and a later age.

I shall adopt here Prestwich's correlation of the Pebble Gravel (*sensu stricto*) with the Westleton Beds, gratefully accepting, too, Solomon's demonstration that the latter are contemporary with some part of the North Sea Drift. No dating difficulty is implicit in this correlation: while the higher level marine 'Pliocene' deposits were rated as Early Pliocene it remained possible as H. B. Woodward, and later, I myself, had suggested, that the Pebble Gravel might be late Pliocene in age. With the Calabrian age of its predecessor fixed, the Pebble Gravel readily falls into place as Pleistocene or 'Early Glacial', as Salter, Sherlock and Bromehead had supposed.

The only respect in which I should now wish to modify my own earlier conclusions concerning the Pebble Gravel is in regard to their fluviatile or marine origin. Impressed by the local belts rich in Lower Greensand chert, evidently attributable to south bank tributaries of an early Thames, I concluded that the deposit as a whole was a fluviatile accumulation, I should now prefer to regard the main sheet of Pebble Gravel as marine, the chert belts marking the course of streams from the Weald across the emergent (?Sicilian) sea-floor. In this connexion I must reject the suggestion that the source of the chert was the Barton Pebble Bed. This contains a little chert at Stanners Hill, Woking, but though much farther from the Wealden source, the chert-bearing Pebble Gravel, north of London, contains vastly more chert, much of it imperfectly rounded. Barrow thought that salt-water hardened such chert and would have facilitated its transport and survival, but I am unable to envisage any plausible mechanism of marine current or wave-action to account for the localised chert-rich belts.

Solomon's demonstration of the association of the Westleton Beds with this North Sea Drift prompts or assists a further correlation. At a date little, if at all, later than that of the Pebble Gravel we have evidence in the North London area of a boulder-clay much older than the Chalky Boulder Clay. I showed a section in this deposit to a party of the Association a year ago, at Mardley Heath near Welwyn. It lies at an elevation of about 350 feet and at least 100 feet above the floor of the vale of St. Albans, covered by the Eastern or Chalky Boulder Clay Drift. Subsequent work has brought to light further significant facts. Dr. I. Cornwall of the Institute of Archaeology succeeded in preparing a thin section of the material to examine its state of weathering and the character of the iron compounds in it. He writes: 'It would therefore appear that the weathering to which the Mardley Heath boulder-clay has been subjected was sufficient, not only for its complete decalcification (which could have happened, given time enough, at existing temperatures), but for destruction of practically all original minerals save quartz, rare micas and still rarer more resistant heavy minerals. This weathering has resulted in the release of clay–minerals, iron and even of silicic acid, suggesting prevailing temperatures significantly higher than those of the present day. Such conditions would be compatible with what we know of those of at least parts of the long Great Interglacial, though it is very doubtful whether they have obtained at any period since then.'

I have also studied with the help of Dr. W. S. Pitcher, the erratics collected on the occasion of our visit. As a whole they suggest a 'Western' provenance including, e.g. a microphyric olivine basalt, comparable with those of the West Midlands, a flow-banded rhyolite, which could be matched in the Pre-Cambrian of the Welsh Borders, and a quartzite which, again, might have come from Anglesey or the Malverns.

Here then we seem to have a true 'Western Drift' and are led to recall former observations of Barrow and Hawkins. The Mardley Heath section gives us a fortunate exposure of material mapped elsewhere by H.M. Geological Survey as 'Pebbly Clay and Sand' or (in part) as 'Glacial Gravel!' Both R. L. Sherlock and G. Barrow, who studied these deposits during the six-inch re-survey of the area (1912–20), were agreed that they were early glacial in age, requiring the presence of ice *or* snow. Barrow (1919, 16) definitely invoked the former. He saw the material well exposed on Chorley Wood Common and though most of the stones in the clay were local (Reading Beds), he found far-travelled stones, including large fragments of vein-quartz scattered evenly through the deposit, as well as rafts of Reading Beds and Pebble Gravel. Even more important were his observations at Cowcroft (1919, 27), near Chesham. Here, again, was a true local boulder clay, yielding unworn flints, fragments of Sarsen and blocks of Puddingstone. The deposits are traversed by overthrust or glide planes which involve also the underlying ground; the Chalk is locally forced some fifty or more feet above its normal flat-lying position. Such effects appear fully to justify his invocation of heavy land-ice. There is no scope for or likelihood of local land-slipping or solifluxion as the origin of these structures. The thrust-planes strike slightly west of north and Barrow considered that the ice here evidenced entered the district 'through and about the side of Goring Gap'. It is therefore important to recall the critical observations made in the last named area by H. L. Hawkins (1923). At an elevation of about 500 feet near Coldharbour immediately above Goring Gap, he found deep trenches cut in the sand of the local Reading Beds, filled with stiff stony clay. The stones included unrolled flints, greywackes, and conglomerates like those of the upper Old Red Sandstone in Herefordshire, together with dark grey and pinkish rhyolites. This assemblage appeared to point to transport from the north-west, including Wales, and Hawkins invoked an ice-sheet from this quarter entering the mouth of the Gap and locally overriding the Chalk escarpment. Little

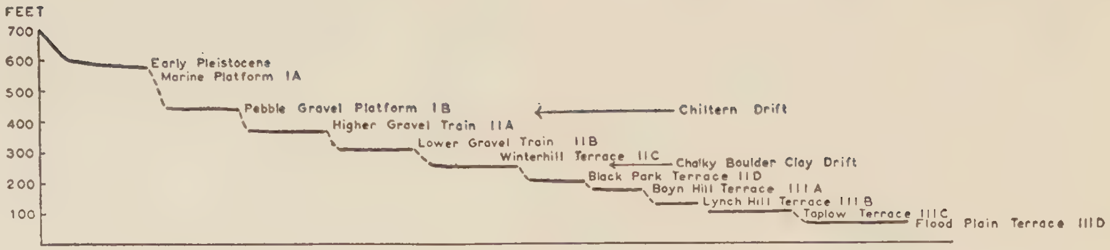


Fig. 2. The terrace sequence in the Middle Thames Valley

notice has been taken of these facts, which again afford no facile escape from the inference of land-ice by way of merely periglacial conditions.

This early 'Western' Boulder Clay, though noted above in the context of our Stage I deposits, belongs strictly to the Stage II group. The main mass of these deposits forms a broad belt extending from Goring Gap north-eastward into Hertfordshire. It is unfortunate that the quarter-inch maps published by the Geological Survey cover only part of this belt and offer no chance to 'see it as a whole'. Nevertheless, it was early perceived by Harmer (1907) that it is the manifest continuation of the belt of Bunter Pebble drift which crossing the line of the Cotswolds near Moreton-in-the-Marsh, then crosses the upper Thames Basin. The essential continuity of the whole train of gravels rich in 'Triassic debris' had indeed been earlier indicated by both Coneybeare and Prestwich. The map accompanying Harmer's 1907 paper effectively illustrates the whole of the country with which we have to deal, east of Goring Gap. It falls conveniently into two sections, the Middle Thames area, between Goring Gap and the lower Colne, and the more easterly area, essentially the Vale of St. Albans. In the former the Stage II belt immediately adjoins that of the Stage III drifts and the deposits of both can be ranged in a continuous series of terrace stages (Fig. 2). In this sequence we take the shingle capping of the Coleshill outlier to represent the Calabrian marine stage. It should be noted that Barrow (1919, 11) did not accept this correlation. More than 100 feet below it Barrow recognised the Pebble Gravel at Hodgemoor Wood. Passing southwards we traverse in turn, in descending order of elevation, the stages distinguished in 1938 as the 'Higher Gravel Train', the 'Lower Gravel Train' and the Winter Hill Terrace. My own work (1938) was in succession to that of Mrs. B. R. M. Ross and has been extended by that of K. Hare (1947) and K. R. & C. E. Sealy (1956). It must, however, be recalled that the first recognition of such high terraces in the Middle Thames area is due to H. J. O. White (1895). The subsequent work is clearly implicit in his pioneer papers. I need not discuss this later work at length, for it figures in recent parts of our PROCEEDINGS. Professor Hare renamed my Lower Gravel Train, the Harefield Terrace, and introduced a Black Park terrace between the Winter Hill and Boyn Hill stages and a Lynch Hill Terrace, below the latter. The successful westward extension of his very precise morphological mapping by K. R. & C. E. Sealy is an eloquent commentary on the imaginings of those who seek to invoke differential earth-movement into a game, already sufficiently complicated. The slightest warping would derange or disjoint terraces which are traceable for long distances, maintaining their relative spacing.

It was this same Western or Middle Thames area which gave birth to Sherlock's attractive hypothesis (1912) of an early Thames as the prime

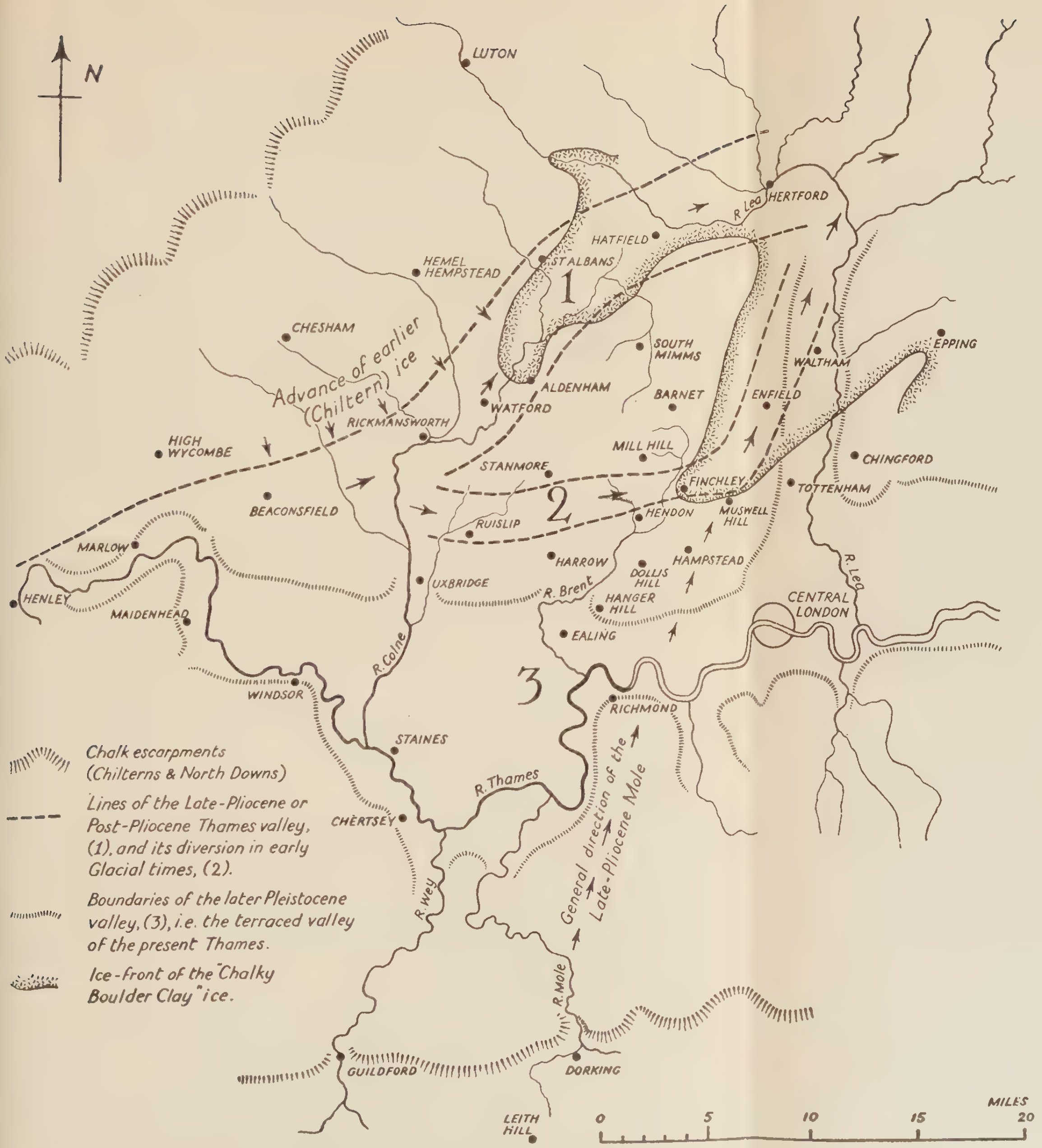


Fig. 3. Former courses of the Thames, north of London

[*To face p.* 122

agent in transporting the 'Bunter Pebble drift' and within this area the hypothesis is entirely acceptable.

In the more easterly area (Middlesex and Herts), the two main drift belts diverge and detailed analysis reveals a complicated sequence of events, summarised in Figs. 2 and 3. The chief member of the Stage **II** drifts in the Vale of St. Albans is the Chalky Boulder Clay and its associated gravels which we may term the 'Eastern Drift'. The western terraces are not in fact traceable into or through the Vale of St. Albans. It appears highly probable that at or just preceding the stage of the Higher Gravel Train the Thames did follow this line, but there are strong indications that it was diverted by glacial agency to a more southerly course (Fig. 3). The details of this act of diversion are lost, but if I am not mistaken, the older or Western Boulder Clay at Mardley Heath rests upon former Thames Gravels of westerly provenance. Even without the evidence contributed by Barrow and Hawkins, one requires an act of glacial interference to account for the facts; a vaguely conceived 'periglacial phase' is not a sufficient substitute. There is, however, a risk of a wholly mistaken interpretation which must here be noted and rejected. Stand, as a party of the Association stood with me last July at Ridgehill, looking across the Vale of St. Albans. The drift which actually floors the Vale is the 'Eastern Drift' and if one seeks an obstructing agent for a former north-easterly flowing Thames, this Eastern ice might seem to be the most convincing candidate for the rôle. But in fact if the Thames ever followed this line it was at a level high above the present floor of the Vale, not lower, near St. Albans, than about 350 feet. It is at or about this level that one seeks the evidence of obstructing ice and duly finds it near Welwyn and elsewhere. The essential 'catch' or confusion in the argument results from the fact that after any such first diversion the floor of the Vale was further lowered, before the advance of the Eastern Ice. This seems to have been the work of a surviving or residual easterly drainage, ancestral to the Lea. The Chalky Boulder Clay protruded two westward lobes, one along the Vale of St. Albans to Aldenham and the other along the diverted or successor valley of the Thames to Finchley (Fig. 3). Clayton & Brown (1958) have recently demonstrated the pro-glacial phenomena associated with this advance, but it must be strongly insisted that this is unrelated to the diversion of the old Thames.

If this reading of the facts is correct we may summarise that from its first northerly line taken upon the emergent floor of the Calabrian sea the Thames has been diverted in two stages, the first the work of an early glaciation of which the details are obscure, the second being clearly the result of the second and major glaciation of the area.

It will be observed that this interpretation enables us to explain the landforms of the North London area, but it leaves one further question without an answer, viz. the course of the older Thames in Essex and the East Anglian region. To this we may now turn. Sherlock was criticised for first taking, as it were, the old Thames to Watford and leaving it there. This point he met in his further work, but he was left in doubt as to its course beyond Ware. At first he was inclined to think that it followed the lower Lea southwards. Later, abandoning this view, he wished to turn it northwards via Cambridge to the Wash. Neither of these possibilities can sustain detailed scrutiny; they are at present without any evidence at all to support them and both are intrinsically unlikely.

It is evidently much more probable that the old Thames continued its course across Essex, but further investigation is hindered by the fact that the whole of central and northern Essex is buried deeply beneath Glacial drift. Any former deposits of the Thames are beneath this drift and any former valley or valleys must be largely or completely filled and obliterated thereby.

It is important to note, however, that our reconstruction in more westerly areas does not depend simply or chiefly on recognising and linking up the deposits of the old river. In varying degrees the old valley-form itself remains recognisable though in the west its floor is at hill-top level. In the North London area, however, the distribution of the Chalky Boulder Clay clearly brings out the general form of the pre-Glacial landscape, for the Aldenham and Finchley ice-lobes occupied pre-existing depressions. There is, however, a source of doubt and confusion here which we must now emphasise. The existing Vale of St. Albans, even stripped of its glacial filling, is not itself the old valley of the Thames, although it follows the same line. If we are correct in concluding that the Thames on this route, or at the stage of the Higher Gravel Train, flowed at a level of about 350 feet it is clear that the Vale was thereafter further deepened to the extent of 150 feet or more before the advance of the Chalky Boulder Clay ice. We infer, therefore, that drainage on the old line was resumed after the first diversion and that a stream draining the Vale eastwards rejoined the diverted Thames near Ware. Yet even when allowance is made for this important fact, it remains true that the form of the surface beneath the Eastern Drift retains the clearest evidence of the former drainage lines and their evolution.

It is encouraged by this fact that the attempt has been made to reconstruct the sub-drift surfaces in Essex and Suffolk (Wooldridge, 1955). This involved the plotting of between two and three thousand well records.

On general grounds it must appear very probable that the early Thames pursued a course across central Essex. This route, indeed, affords the only probable outlet to the contemporary coast before the first diversion by the Chiltern ice, but of the details of this early course we have at present no evidence. At the Lower Gravel Train stage we are on somewhat surer ground. We have inferred that at this time the drainage of the Finchley depression met the revived or resumed drainage along the Vale of St. Albans in the neighbourhood of Ware. Eastwards there opens the broad trough of the lower Stort valley and, even if we confine our study to the form of the present drift-covered surface, there is a clear suggestion that the combined drainage passed eastwards through this trough towards Chelmsford and the coast. The whole area, however, is thickly drift-covered and we are at present without any adequate stratigraphical details of the drift. There has been no six-inch revision of the Epping sheet or of the country to the north and east of it and the only geological maps available are the hand-coloured sheets now nearly a century old. These indicate sufficiently well, in broad terms, the distribution of the great sheet of boulder clay, of the gravels associated with and for the most part underlying it, and of the later river deposits then regarded as 'Post-Glacial'. It cannot be doubted that much detail remains to be recorded and that a more complicated classification of the drifts would result from detailed survey. Meanwhile it is possible to obtain some evidence on the form of the sub-drift surface from well records.

The lower Stort valley between Roydon and Harlow is cut wholly in drift which obviously fills a wider depression trending from west-south-west to east-north-east. This is bounded on the south by the ridge (over 300 feet) of Epping Long Green; on the north boulder clay is continuous over the high ground and no clear limit to the depression can be seen in the surface contours. Well records show, however, that the floor of the main trough beneath the drift occurs at levels between about 145 and 170 feet. Recent work by K. M. Clayton (1957) on the evidence yielded by the many borings made for the New Town of Harlow reveals that the most extensive flat surface beneath the drift is at 160–165 feet near Netteswell. Here we seem to have well-preserved fragments of the floor of the former Thames Valley. The depression broadens eastwards into the country about the upper Roding Valley. Here there are records of the sub-drift floor at 145 feet at Abbess Roding and 106 feet at Berners Roding.

North-eastwards from Chelmsford the form of the floor becomes complicated and more difficult to interpret. It descends well below 100 feet and even below sea-level at Witham and Kelvedon. Here, however, we are south of the main boulder clay edge and the date of the 'floor' revealed is uncertain. There may possibly be a 'sub-drift channel' in this neighbourhood. Alternatively, we may be dealing with the results of river erosion and aggradation of a much later date. The only fact on which we may certainly depend is that the boulder clay itself descends below 200 feet in the Chelmer and Blackwater valleys and we may define a broad depression trending north-east towards Colchester. To the south lies the high gravel mass of Danbury and the continuing ridge of Wickham Bishops and Tiptree. Along this ridge the sub-drift floor descends from 250 feet at Danbury to 185 feet at Tiptree. Northwards of the main trough the sub-drift surface climbs more slowly, reaching the 200-foot level near Dunmow and Braintree. In this neighbourhood large areas of the floor lie at or about 200 feet, but lower levels are recorded in the vicinity of all the main valleys. As a whole this great mid-Essex trough is evidently a continuation of the lower Stort depression.

We may return now to the question we asked at the outset concerning the seaward course of the Thames at the stage of the Lower Gravel Train. It is clear that, considering the evidence in plan, there is considerable support for the hypothesis of a main drainage line across central Essex, with tributaries entering from the north and the south. The present rivers Stort, upper Roding, Chelmer, Brain, Pant–Blackwater and Colne probably follow lines close to those of their ancestors. On the south the Wid and Sandon Brook remain as descendants of earlier northward-flowing streams, while the lower Roding between Chigwell and Fyfield, north of Ongar, may well mark the line of another such tributary, since reversed by capture and southward diversion to the present lower Thames drainage. It will be noted that the eastern part of the Finchley Depression is parallel with the central section of the Roding Valley and may well have originated as a similar south bank tributary of an earlier axial line of drainage even though it later served for the diverted Thames.

If we tentatively accept this basic pattern of drainage we are still left in doubt as to whether the ultimate seaward outlet was in the neighbourhood of the present Stour or the Blackwater estuary or whether indeed each may not be a relic of a former course of the Thames. On the whole it appears more probable that the exit at the Lower Gravel Train stage was in the vicinity of the Blackwater estuary.

Passing now to the Stage **III** deposits, I cannot add usefully to the conclusions reached by King & Oakley (1936). They may be summarised thus: The earliest deposits of the Boyn Hill terrace (the 'Lower Gravels' at Swanscombe) were accumulated following a phase of planation which formed the rock 'floor' on which they rest at about seventy feet O.D. The included fossils indicate a temperate climate. There then ensued a negative change of base-level and the erosion of a deep channel of which the floor stands at twenty feet O.D. near Swanscombe and below sea-level at Clacton. In the following phase the channel was filled as sea-level rose and the deposits finally extended beyond its lip so as to rest upon the Lower Gravel at Swanscombe. At this time, therefore, the flood-plain rose higher than in the early Boyn Hill phase and the equivalent sea-level is estimated to have stood at about 100 feet O.D. It is particularly to be noted that the acceptance of this pronounced phase of aggradation implies that lower-lying deposits may be older than those at higher levels.

Thus gravels and brickearths at Ilford and Stoke Newington which occur at what would normally be considered the 'Taplow' level are, in fact, assigned to a stage of the Boyn Hill aggradation.

The great oscillation of sea-level, as deduced by King & Oakley, involving the cutting and subsequent filling of a deep channel, indicates the pattern of later events. The succeeding fall of base-level led to a renewed deepening of the valley to below its present floor, uncovering the Boyn Hill ledge with its composite covering of deposits, as a terrace, but locally sparing the lower part of the infilling of the former channel. Upon both these sets of deposits is found superimposed a well-marked layer of Chalky sludge (Coombe Rock), the product of solifluxion in a climate of glacial severity. Further down-cutting followed, in which parts of the sludge-sheet were removed; the succeeding aggradation built up the thick gravel of the Taplow stage by the end of which sea-level is estimated to have reached about sixty feet O.D. There followed a widespread phase of brick earth formation reflecting a steppe climate in which windblown dust was accumulated as loess or arrested by marshes or standing water to give water-laid loams.

Three further phases of down-cutting followed by aggradation are evidenced in the succeeding deposits. First was formed the rock-floor of the Upper Flood Plain Terrace: the lower part of the deposits which rest upon it yield clear fossil evidence of an Arctic climate (Ponders End Stage) and are associated locally with solifluxion gravels which mark the return of 'periglacial' conditions. The ensuing fall of sea-level led to the cutting of another deep channel, the 'Buried Channel', with its floor in places as much as 100 feet below O.D. During the cutting of this gorge it is believed that solifluxion gravels continued to descend the valley slopes, but with the return of a warmer climate and a rising sea-level, aggradation was resumed and the channel was filled with gravel to a height above that of the existing alluvial flood-plain. The upper surface of the 'fill', where this protrudes above the alluvium, constitutes the Lower Flood Plain Terrace. The alluvium itself attains locally a thickness of fifty feet, and this has been taken to imply the cutting of still another channel in the earlier gravel 'fill' and its subsequent filling by aggradation.

In conclusion, my endeavour in writing this lecture has been to present a general picture, eschewing local detail, without which, however, none of the conclusions I have reported or commended could have been reached. Having myself written a good deal on the subject before, I have had to face the threat or inhibition thus expressed by Lewis Carroll's Red Queen when she said 'It's too late to correct it: when you've once said a thing, that fixes it and you must take the consequences'. It is over-easy to dismiss the conclusions of others in preferring one's own. The poet's admonition gets reversed and becomes 'Courage in another's trouble, kindness in your own'.

Let me say, therefore, that I am not so foolish as to imagine that I have said the last word on our subject or even foreshadowed the beginning of the end of our long-term task to observe and interpret the ground around and beneath us in the London district. To my younger friends and successors I would say: 'Go to the Atlantic Ends, if you must, but remember that the sewer trench at the end of the road may show something much more important and waiting only for an observer.' 'All things that pass are wisdom's looking glass'—particularly temporary sections.

Though I have taken occasion this evening to correct a few of my own mistakes, I have been more concerned as befits this centenary year to look back to the pioneers. If I had to introduce an enquiring visitor to the fascination and the complexities of our local drift geology I should place in his hands, Prestwich's (1890) Westleton paper; A. E. Salter (1905) 'On the Superficial Deposits of Central and Southern England; H. B. Woodward (1909) 'Geology of the London District'; and G. Barrow (1919) 'Some Future Work for the Geologists' Association'.

In those thirty years most of the crucial questions were asked and some of them answered.

The other works I have specially mentioned are taken from our recent PROCEEDINGS which I hope are the forerunners of many others.

As G. K. Gilbert wrote: 'When the work of the geologist is finished and his final comprehensive report is written, the longest and most important chapter will be upon the latest and shortest of the Geological periods.'

We are far from such final report. . . .

REFERENCES

BARROW, G. 1919. Some Future Work for the Geologists' Association. *Proc. Geol. Ass., Lond.*, **30,** 36.

CLAYTON, K. M. 1957. Some Aspects of the Glacial Deposits of Essex. *Proc. Geol. Ass., Lond.*, **68,** 1.

——— & J. C. BROWN. 1958. The Glacial Deposits round Hertford. *Proc. Geol. Ass., Lond.*, **69,** 103.

DAVIES, A. M. 1953. A Preliminary Survey of the Sarsens of the Chilterns. *Proc. Geol. Ass., Lond.*, **64,** 1.

HARE, F. K. 1947. The Geomorphology of part of the Middle Thames. *Proc. Geol. Ass., Lond.*, **43,** 294.

HARMER, F. W. 1907. On the Origin of certain Cañon-like Valleys. *Quart. J. geol. Soc. Lond.*, **63,** 494.

HAWKINS, H. L. 1923. Excursion to Goring Gap. *Proc. Geol. Ass., Lond.*, **34,** 56.

KING, W. B. R. & K. P. OAKLEY. 1936. The Pleistocene Succession in the Lower parts of the Thames Valley. *Proc. Prehist. Soc.*, **1,** 52.

MCKENNY HUGHES, J. 1868. The two plains of Hertfordshire and their Gravels. *Quart. J. geol. Soc. Lond.*, **24,** 283.

PRESTWICH, J. 1890. On the Westleton Beds and their extension inland. *Quart. J. geol. Soc. Lond.*, **46,** 123, 155.

SALTER, A. E. 1905. On the Superficial Deposits of Central and Southern England. *Proc. Geol. Ass., Lond.*, **19,** 1.

SEALY, K. R. & C. E. SEALY. 1946. The Terraces of the Middle Thames. *Proc. Geol. Ass., Lond.*, **67,** 369.

SHERLOCK, R. L. & A. H. NOBLE. 1912. On the Glacial Origin of the Clay-with-Flints of Buckinghamshire and on a former course of the Thames. *Quart. J. geol. Soc. Lond.*, **68**, 199.

SOLOMON, J. D. 1935. On the Westleton Series of East Anglia. *Quart. J. geol. Soc. Lond.*, **91**, 216.

WHITE, H. J. O. 1895. On the Distribution and Relations of the Westleton and Glacial Gravels in parts of Oxfordshire and Berkshire. *Proc. Geol. Ass., Lond.*, **14**, 27.

WOODWARD, H. B. 1909. Geology of the London District. *Mem. geol. Surv. U.K.*

WOOLDRIDGE, S. W. 1938. The Glaciation of the London Basin. *Quart. J. geol. Soc. Lond.*, **94**, 627.

——— & H. C. K. HENDERSON. 1955. Some Aspects of the Physiography of the Eastern Part of the London Basin. *Inst. Brit. Geog.*, **21**, 19.

ZEUNER, F. E. 1945. *The Pleistocene Period.* Roy. Soc. Publn.

———. 1959. *The Pleistocene Period.* 2nd Edition, Hutchinson, London.

Editor's Note. The Council of the Association gratefully acknowledge the kindness of the Prehistoric Society in permitting the use of the blocks (Figs. 2 and 3) from their *Proceedings* of 1957.

The Tectonics of the 'Great Ice Chasm', Filchner Ice Shelf, Antarctica

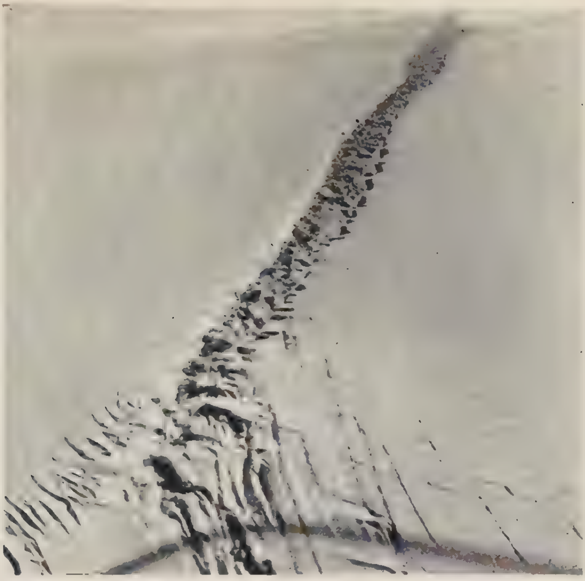
by GILBERT WILSON

Received 1 May 1959; read 3 July 1959

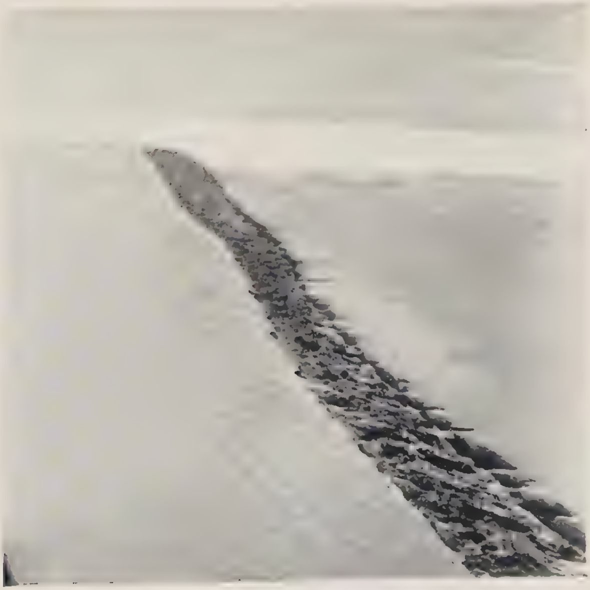
ABSTRACT: The Commonwealth Trans-Antarctic Expedition, 1955–8, observed that the Filchner Ice Shelf was traversed by a straight east–west zone of brecciated ice—the 'Great Ice Chasm'—about forty miles south of Shackleton. Analysis of the crevasse patterns at the eastern end of the Chasm indicates that the brecciated zone probably resulted from a wrench- or tear-faulting movement, in which the northern side moved westwards relative to the southern. The frictional drag caused by the strong westward current of the Weddell Sea on the base of the northern part of the floating ice-shelf is considered to have been largely responsible for the formation of the Chasm.

EVEN AS WE ARE often informed that truth is stranger than fiction, so is it uncommon for Nature to provide us with a clear, larger scale and more complete demonstration of some simple tectonic mechanism than we, ourselves, can produce by experiment. This, however, she seems to have done at the eastern end of the 'Great Ice Chasm' which runs east and west across the Filchner Ice Shelf, about forty miles south of Shackleton, Antarctica (Fuchs & Hillary, 1958, Map 2, p. 100, and photograph No. 6, between pp. 20–21). This Chasm, also referred to as the 'Grand Chasm', has a total length of about sixty miles (100 km.), and a maximum width of about three miles (5 km.). 'The jumbled ice mass in the bottom lies 175 feet (54 m.) below the shelf level . . . but the rupture must extend through the entire shelf. . . .' (Neuburg, Thiel, Walker, Behrendt & Aughenbaugh, 1959, 114).

The photograph reproduced here in Plate 6 A shows the relatively smooth surface of the shelf broken by a long straight zone of intensely shattered ice which has a length, within the area shown, of at least fifteen miles (24 km.). It has an estimated width of 200 to 300 yards near its eastern end, and it gradually widens to a mile or more before it disappears beneath the clouds in the west. The near or eastern end of the Chasm is broken up into a complex of crevasses which can be resolved into two main types or groups. Those which continue the left or south margin of the Chasm are curved and sigmoidal in shape; they are tight at the ends, and become wider or gaping in their central portions. Those to the right or north of the Chasm form a system of straight-line fractures which show little variation in width along their lengths, except for a natural tapering as they die out. This system can in turn be divided into two sets: the more prominent



A. The eastern end of the 'Great Ice Chasm', looking west. Sigmoidal tension gashes to the south (left), and straight-line shear fractures to the north (right). The length of the Chasm shown is about fifteen miles (Photo No. 2342)



B. The 'Great Ice Chasm', looking west. Straight-line shear fractures, locally curving into the direction of tension fractures, show as faint lines on the south (left) side of the Chasm. The SW.–NE. orientation of the seracs in the Chasm can be seen in the foreground (Photo No. 2345)

(Both photographs reproduced by kind permission of the Commonwealth Trans-Antarctic Expedition)

appears to trend roughly between east-north-east and north-east, and the second makes a large angle with it (Plate 6A). Parallel to the second set of fractures are slight undulations or drifts which in places cross, or are cut, by other crevasses. Similar (?) drifts can be faintly seen on the surface of the Ice Shelf itself. Crevasses which are sub-parallel to the prominent fractures on the north side of the Chasm also occur on its south side, but as they approach the Chasm edge they curve in towards it. They show as faint lines on Plate 6B. In addition the seracs within the Chasm itself can be seen in the same photograph to have a general SW.–NE. trend. This trend is even more marked in other air-photographs taken by the Trans-Antarctic Expedition (Photo K.5931).

The fracture pattern as a whole is monoclinic, and seems to conform closely to the theoretical pattern that might be expected to develop if the Chasm were a zone of wrench-faulting, on which the right-hand side (north) had moved to the west relative to the left-hand side (south) which moved to the east. This suggestion is primarily based on the impression that the sigmoidal crevasses represent tension gashes which had been initiated, opened up, and partially rotated by a continuous left-handed movement along the main zone of fracture. The prominent straight-line crevasses to the north of the Chasm would fit into the structural pattern equally well as tensional fractures which have not been rotated, or as planes of break in the ice shelf parallel to a direction of maximum shearing stress. Which is the more probable largely depends on the true angular relationship between the crevasses and the line of the Chasm. It is therefore necessary briefly to consider the effect of foreshortening due to perspective and to the tilt of the camera, which together have yielded the *apparent angles* now seen between the crevasses and the Chasm in Plate 6, A and B.

If the position of the aeroplane relative to some fixed points on the ground, its height, and the tilt of the camera were accurately known, it would be possible to work out the *true angles* between the crevasses and the Chasm from the apparent angles seen in the photographs. The height from which the pictures were taken was about 1000 to 1500 feet above the ice-shelf, but the other necessary information is unfortunately unobtainable. Two possible lines of procedure present themselves. Firstly, one can make a diagrammatic plan of the Chasm with its crevasses shown at various angles (Fig. 1B); then, from this plan one can construct a series of perspective drawings corresponding to different positions of the aeroplane, and note which drawing and which set of crevasse lines most closely accord with the original photograph (Fig. 1A and Plate 6A). Alternatively, and more easily, one can view the plan on the ground-glass focusing screen of a plate-camera whose height and angle of line of sight can be adjusted. This method not only shows the plan in perspective, but enables one to make allowance for the original tilting of the camera in the aeroplane. The

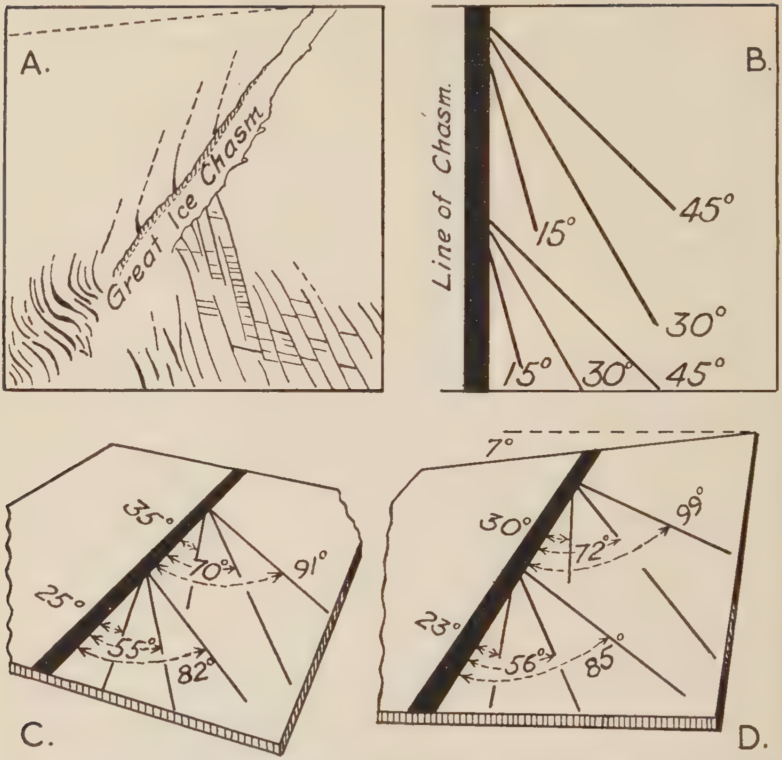


Fig. 1. Showing diagrammatically the relationship of true angles to apparent angles between the line of the Chasm and its crevasses, as seen in oblique air-views. All traced from photographs.

A. The eastern end of the Chasm with its crevasses, taken from Plate 6 A. The dotted line near the top indicates the general tilt of the horizon in the photograph

B. Diagrammatic plan of the Chasm with crevasse-lines drawn at different angles

C. and D. Oblique air-views of the plan B. In C the line of sight of the camera was inclined at 25°. In D, it was at 35°, and the plan was tilted at 7° to the left to give a tilted horizon line as in A

model crevasse patterns can then be photographed. The set-up is very similar to that described by G. D. Hobson (1942).

Comparisons of the oblique air-views of the model with the actual plan are instructive:

(i) The true angles between the lines representing the crevasses and the edge of the Chasm are much smaller than the apparent angles seen in the oblique air-views.

(ii) The prominent crevasses in Plate 6 A lie at an angle of much less than 45° to the Chasm, probably little over 20°. The corresponding straight-line crevasses to the south of the Chasm (Plate 6B) make an angle of not more than 15° to the main zone of fracture.

(iii) The apparent angles in the oblique air-view of a line having a true angle of 45° to the Chasm in the model, lie within a few degrees on either side of 90°, as shown in Fig. 1, C and D.

(iv) The short, less prominent straight-line crevasses in Plate 6A converge towards a vanishing point far away to the left of the line of the Chasm. They must therefore strike nearly perpendicularly to the Chasm itself, and at about 70° to the more prominent set of crevasses.

The crevasse system to the north of the Chasm thus roughly corresponds, in its angular relationship to the main zone of fracture, to the 2nd Order right and left wrench-faults which Moody & Hill (1956) find are associated with major transcurrent faults. However, the crevasse system as a whole, north and south combined, conforms even more closely to the various fracture pattern which can be obtained in Riedel's well-known experiment (Riedel, 1929).

This experiment has been repeated and quoted by many workers (Hills, 1940; Blyth, 1950; Shainin, 1950; Wilson, 1952; Cloos, 1955; de Sitter, 1956; Kanungo, 1956, and others). It is simple to demonstrate, and consists of two boards laid side by side and covered by a flat cake of wet clay. A shear is then imparted to the clay layer by moving one board relative to the other along their edges of contact. The stress system which results from this movement is shown in Fig. 2A. The moving board imparts a shearing couple Sc_1, Sc_1, to the clay cake, in which the anti-clockwise torque of the couple must—if rotation does not occur—be balanced by an induced secondary clockwise torque or couple acting at right-angles to the first, Sc_2, Sc_2. Such a stress system can be resolved into two principal stresses (Fig. 2B) of compression (*PP*) and tension (*TT*) at right angles to each other. Rupture of the clay cake may occur by tension, with the formation of gaping fractures (*t*) which strike at 45° to the main line of slip and are normal to the tensional stress *TT* (Fig. 2C). Alternatively (Fig. 2D), failure may occur along fractures more or less parallel to the directions of maximum shearing stress—*Sa* and *So*; these theoretically should lie symmetrically at angles of less than 45° on either side of the direction of maximum compression *PP*. In Riedel's experiments failure along both directions of shear did not develop, and the fractures formed only at a small angle with the main line of slip and so corresponded to *Sa*. This angle rarely exceeds 20°. The shear-planes *So*, which should lie at a much larger angle to the main line of slip than do the *Sa*-planes can seldom be developed. Both sets were however produced together by Ernst Cloos (1955), and in the Geological Laboratories of the University of Wisconsin when a block of limestone was fractured by rotational shear under considerable retaining pressure (Leith, 1923, fig. 11B; Wilson, 1946, fig. 52, c). Failure by both tension and shear together in the same experiment is possible, and a good example of it has been illustrated by Cloos (1955, Plate 3).

The crevasse system at the eastern end of the Chasm suggests that failure by both tension and shear has occurred. The sigmoidal, gaping crevasses on the left (south) side of the Chasm look like typical tension fractures, as illustrated by Shainin (1950), such as would be formed by a tensional stress operating in the north-west and south-east quadrants. The two sets of intersecting straight-line crevasses on the right-hand (north) side of the main zone of shattering show a fracture pattern that would conform to the directions of maximum shearing stress if the ice were subjected to a maximum compression acting in a SW.–NE. direction, combined with a

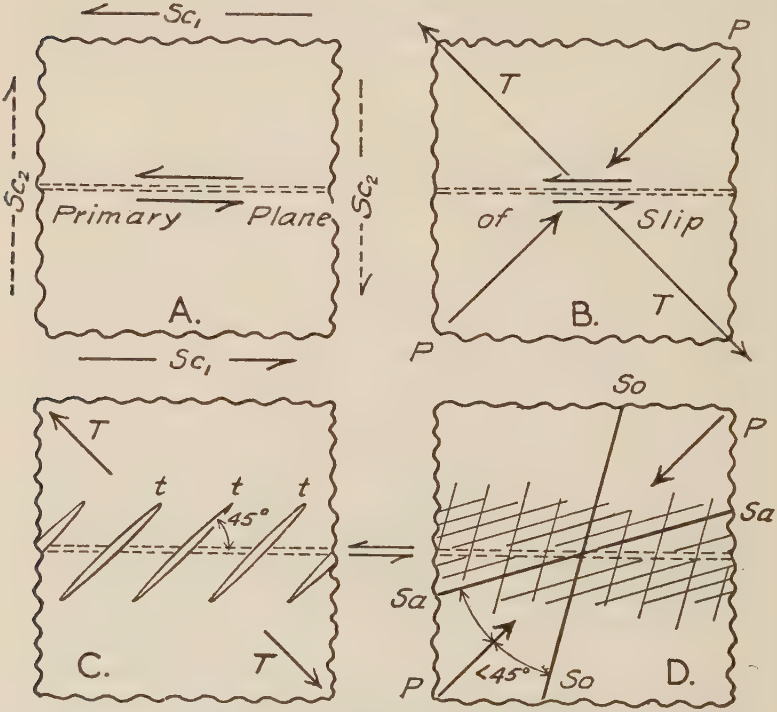


Fig. 2

A. The stress system developed in an element subjected to a couple Sc_1—Sc_1 acting counterclockwise along a primary plane of slip

B. The resolution of the two couples Sc_1 and Sc_2 into principal stresses: T = Tension, P = compression

C. The development of *en échelon* tension gashes (t) at right angles to the tensional stress (T) and at 45° to the primary plane of slip

D. The theoretical directions of planes of shearing, Sa and So, at less than 45° to the maximum compressive stress, and their relationship to the primary plane of slip tensional stress acting in the opposite quadrants. The straight-line crevasses which lie to the south of the Chasm (Plate 6B) also conform to this stress distribution. Hence, the orientations of the principal stresses on both sides of the Chasm are in accord, even though the styles of fracturing of the shelf ice are different.

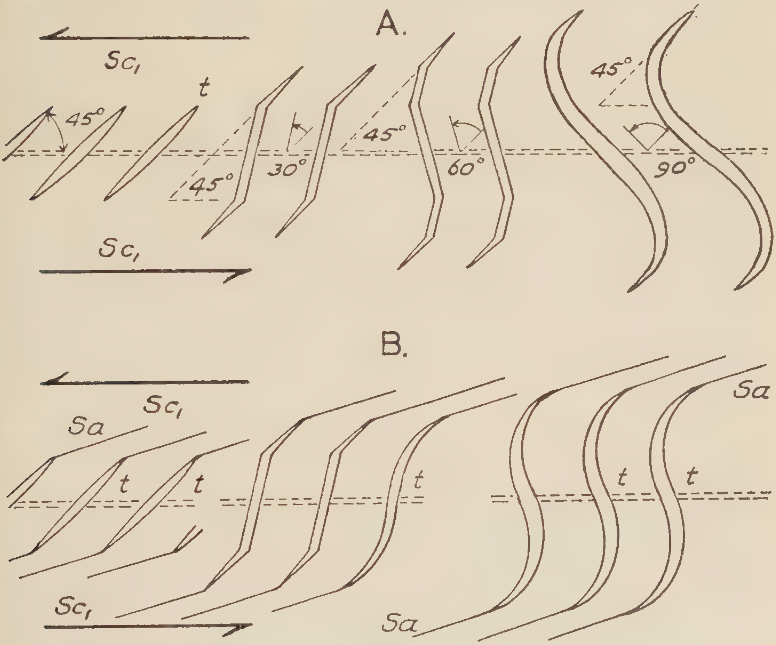


Fig. 3

A. The development of sigmoidal tension gashes; the sigmoidal form results from the rotation of the inert material between the fractures while the ends of the fractures continue to develop at 45° to the plane of slip

B. The pronounced sigmoidal form of tension fractures developed partly by rotation and grading into planes of shear

The strong curvature of the sigmoidal crevasses is noteworthy. Shainin (1950) explained that the sigmoidal form of tension gashes is commonly the result of a rotation, from the original 45° position, of the inert rock-matter lying between pairs of fractures while the fractures themselves are slowly developing during a prolonged period of movement. It is only the material between the actual fractures which is rotated and the tapering ends of the latter continue to be extended at 45° to the primary direction of slip (Fig. 3A). The tapering ends of curved crevasses of the Chasm, however, swing even further around beyond the 45° angle, until they are in fact continued in the straight-line crevasses which make a small angle with the line of the

Chasm on its southern side. It appears likely therefore that the strong curvature of these sigmoidal crevasses has resulted from the combined effects of failure by tension accentuated by partial rotation and by failure by shear, the two appearing more or less simultaneously and grading one into the other (Fig. 3B and Plate 6B).

One gets the impression, from the photograph Plate 6A, that the centre-line of the zone of sigmoidal tension gashes is nearly colinear with the southern edge of the Chasm itself, and may mark its incipient continuation. This is further supported by the roughly SW.–NE. trends of the seracs within the Chasm itself. These likewise conform to the theoretical direction of tensional fracturing between the walls of the Chasm (Plate 6B, and Fig. 2C).

The remarkable straightness of the Chasm itself for some sixty miles, and the width of shattered ice which forms the feature, together with the evidence outlined above based on the monoclinic fracture patterns of the local crevasses, all indicate that the Great Ice Chasm, at least at its eastern end, is a tear or wrench fault, on which the movement was left-handed or sinistral. That is, the north side moved west relative to the south side.

The Trans-Antarctic Party '. . . believed this [the Chasm] to be caused by the movement of the ice shelf past an area of higher, snow-covered ground that had been observed from the air many miles to the west and south' (Fuchs & Hillary, 1958, 149) and the conclusions reached in this paper support this suggestion. It was also observed that the pack ice of the Weddell Sea was continually moving westward despite the effect of variable winds: 'It therefore seems that the current sweeping down the east coast of the Weddell Sea and along the edge of the ice shelf is strong enough to overcome the usual drift of the sea ice with the wind' (Fuchs & Hillary, 1958, 42). Neuburgh *et al.* (1959) also noticed that this current jams the pack ice against the eastern coast of the Palmer Peninsula, which forms the western margin of the Filchner Ice Shelf, some 450 miles (720 km.) west of Shackleton. This current, flowing towards the west, would by fractional drag on the base of the floating ice shelf simulate the moving board below the clay cake of Riedel's experiment, and the westward drift would tend to produce a left-handed (sinistral or counterclockwise) couple in the ice which is anchored somewhere in the south. The main concentration of stress in the ice would be controlled partly by the location and shape of the anchorage in the south and west, and partly by the area of the underside of the floating shelf-ice exposed to the Weddell Sea currents. These are matters beyond the scope of the present paper. Nevertheless, the Great Chasm probably marks the zone which, in Riedel's experiment, corresponds to the line of junction of the two boards, though not necessarily to the 'strandline' or boundary between the floating and grounded ice.

For once it seems that in Tectonic Geology we are given definite evidence of the direction and the nature of the motive force responsible for the structure. It is of interest, not to say satisfaction, that the movement on the Great Ice Chasm of the Filchner Shelf, as deduced from the pattern of its crevasses, corresponds in direction and sense to the movement of the Weddell Sea current, which was probably the cause of the effect that can be seen.

ACKNOWLEDGMENTS

The preparation of this paper has been greatly assisted by the interest and encouragement which I have received from members of the Commonwealth Trans-Antarctic Expedition. Sir Vivian Fuchs most kindly supplied the photographs here reproduced in Plate 6. Both he and Dr. Harold Lister read over a preliminary draft of the paper and suggested its publication, while Dr. Jon Stephenson has discussed various points with me by air-mail from Lahore, Pakistan. To Dr. J. F. Nye, of Bristol I am most grateful for helpful criticism and comments. I have also been encouraged and assisted by Professor H. H. Read, F.R.S., who is a member of the Committee of Management of the Commonwealth Trans-Antarctic Expedition, and by my colleagues at the Imperial College.

DISCUSSION

SIR VIVIAN FUCHS: 'May I say how pleased I am to have heard Dr. Wilson's explanation of the formation of The Great Ice Chasm. Unfortunately we did not think of this when we were on the spot or we would have taken vertical air photographs and thereby made his interpretation easier.

'There are two small points upon which I might comment. First, there is a considerable mass of ice pouring off the Touchdown Hills towards the west, which must exert a great force upon the northern part of the Filchner Ice Shelf. Second, the ice shelf (1300 feet thick) almost certainly has considerable relief on its undersurface which would allow the strong and constant current to exert a greater thrust to the west than if the surface was smooth. Both these facts support Dr. Wilson's argument.'

DR. GILBERT WILSON, in a written reply, took the opportunity of again thanking Sir Vivian Fuchs for the interest he had shown in the paper. The fact that a large mass of ice was pouring off the Touchdown Hills, which lie to the north-east of the eastern end of the Chasm, would certainly tend to accentuate the shearing stress in the shelf-ice in that area. If the crevasse systems pictured in the photographs were confined to the eastern end of the Chasm, it might even be considered that the moving ice from the Touchdown Hills was, itself, responsible for the fracture pattern on the north side of the Chasm. That this ice could be responsible for the Chasm as a whole seemed very unlikely; and Dr. Wilson was glad to learn from Sir Vivian of the irregular relief of the lower surface of the Filchner Ice Shelf, as this supported the hypothesis outlined in the paper.

REFERENCES

BLYTH, F. G. H. 1950. The Sheared Porphyrite Dykes of South Galloway. *Quart. J. geol. Soc. Lond.*, **105**, 393.

CLOOS, ERNST. 1955. Experimental Analysis of Fracture Patterns. *Bull. geol. Soc. Amer.*, **66**, 241.

FUCHS, SIR VIVIAN & SIR EDMUND HILLARY. 1958. *The Crossing of Antarctica*, 338, London.

HILLS, E. S. 1940. *Outlines of Structural Geology*, London.

HOBSON, G. D. 1942. A Method of Constructing Perspective Diagrams of Mine Workings. *Trans. Inst. Min. Met.*, **51**, 311, London.

KANUNGO, D. 1956. *Structural Geology of the Torridonian, Lewisian and Moinian Rocks of the Area between Plockton and Kyle of Lochalsh, in Wester Ross, Scotland.* Ph.D. Thesis, Univ. of London.

LEITH, C. K. 1923. *Structural Geology*, New York and London.

MOODY, J. D. & M. J. HILL. 1956. Wrench-Fault Tectonics. *Bull. geol. Soc. Amer.*, **67**, 1207.

NEUBURG, H. A. C., E. THIEL, P. T. WALKER, J. C. BEHRENDT, & N. B. AUGHENBAUGH. 1959. The Filchner Ice Shelf. *Ann. Assoc. Amer. Geogr.*, **49**, 110.

RIEDEL, W. 1929. Zur Mechanik geologischer Brucherscheinungen. *Zbl. Miner. Geol. Paläont.*, Abt. B (1929), 354.

SITTER, L. U. de. 1956. *Structural Geology*, New York and London.

SHAININ, V. E. 1950. Conjugate Sets of *en Échelon* Tension Fractures in the Athens Limestone at Riverton, Virginia. *Bull. geol. Soc. Amer.*, **61**, 509.

WILSON, GILBERT. 1946. The Relationship of Slaty Cleavage and Kindred Structures to Tectonics. *Proc. Geol. Ass., Lond.*, **57**, 263.

———. 1950. A Quartz Vein System in the Moine Series near Melness, A'Mhoine, North Sutherland, and its Tectonic Significance. *Geol. Mag.*, **89**, 141.

Pleistocene Geology of the Country around Bromsgrove

by M. E. BARTON

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ABSTRACT: The Pleistocene Deposits of a triangular area in Worcestershire, enclosed by the villages of Romsley, Barnt Green and Upton Warren, are divided into Older and Newer Drifts. The Older Drifts are of higher level and consist of gravels below and a boulder clay above. The Newer Drifts are valley terraces deposited in the valleys, cut below the Older Drift level. Five such terraces are recognised and they are correlated with the terrace stages established by Professor Wills for the Severn Valley. Finally, the nature of the sub-Older Drift surface is described. This shows a deep, buried channel which is interpreted as an ice marginal overflow channel.

INTRODUCTION

THE REGION studied comprises a triangular area between the villages of Romsley (962798),[1] Barnt Green (008736) and Upton Warren (931675). This is the drainage area of the upper part of the River Salwarpe.

Only passing references have been made to the Pleistocene Geology of this area. Strickland (1842) noted the occurrence of drift gravels exposed in cuttings of the Birmingham–Gloucester railway line. In 1875 the Erratic Block Committee of the British Association meeting at Bristol reported on erratics occurring in the Bromsgrove district. They recorded ninety-three felspathic boulders and specified three varieties: (1) compact, (2) containing small porphyritic crystals and (3) a decided ash. At this meeting they referred to the fact that they had not observed any granites in the district. At the Dublin meeting of 1878 they described the Bromsgrove boulders as an overshot load from the great Arenig stream of erratics which had found its way through the Llangollen Vale into the Central Plain of England. In 1888 Crosskey recorded three Welsh felsites at 890 feet on Romsley Hill and made use of them to demonstrate the theory of land ice to Professor Carvill Lewis.

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[1] Grid References are found in the 100 km. squares.

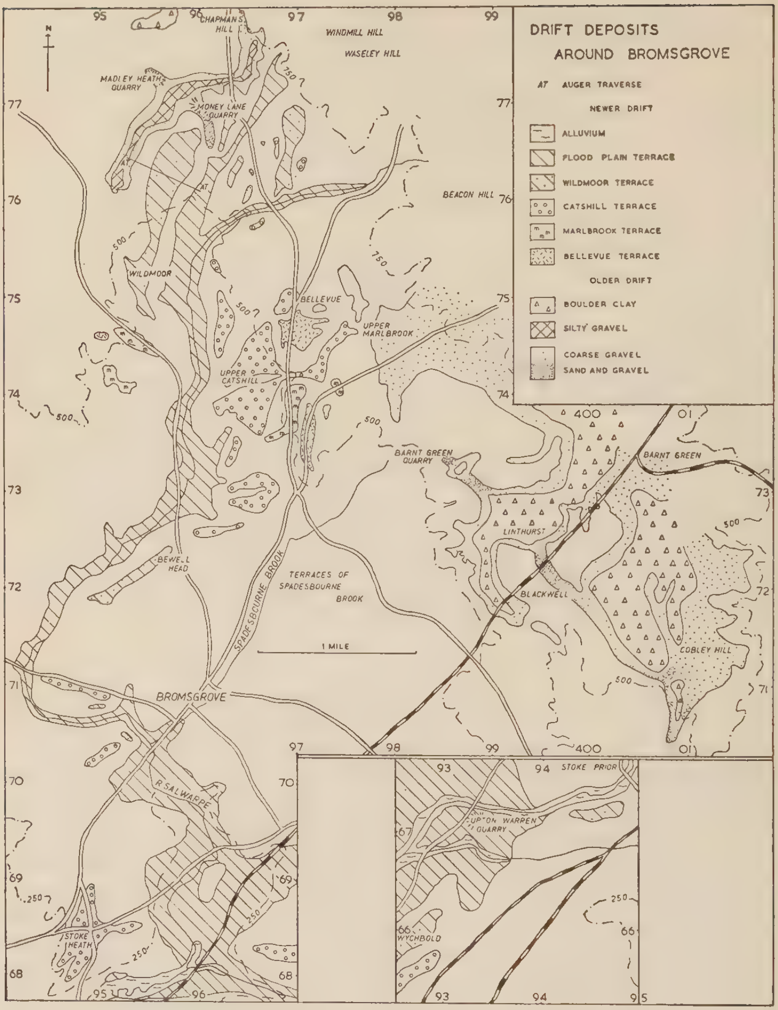

Fig. 1

Of particular relevance to a study of the area are the papers of Wills regarding the evolution of the Severn. In his 1938 paper he gives a systematic account of the river terraces and divides them into six levels. In this paper he included the work of Reeves who mapped the terraces of the River Salwarpe upstream to Upton Warren. These were briefly described and then correlated with those of the Severn. He also appended a profile of the Salwarpe up to Wildmoor but made no attempt to describe or correlate the drifts beyond Upton Warren, though he had recorded observations about them which he subsequently placed at my disposal.

Detailed study of the drifts in the Coventry, Rugby and Leamington area by Shotton has demonstrated the former existence of a proglacial lake between Leicester and Bredon Hill (Lake Harrison) and has led to a reinterpretation of the history of the Avon Valley. In the light of this, work has been done by Pickering (1957) in the South Birmingham area and by Bishop (1958) in the Cotswolds. Consequent on this recent work, a thorough investigation of drifts on the Clent–Lickey ridge and the Ridgeway had become necessary and it was with a view to starting this that the present work has been done.

2. GENERAL SEQUENCE

The River Salwarpe rises on the south side of the Clent–Lickey ridge and flows south-westwards through Bromsgrove, to join the Severn. The eastern watershed of the Salwarpe and its tributaries is formed by the Ridgeway, to the east of which is the River Arrow flowing to the Avon. To the west, an irregular ridge separates the Salwarpe system from the Hoo and Elmley Brook drainage areas. The Clent–Lickey ridge is formed by a core of Enville Sandstone and Breccia with small inliers of older rocks on the Lickey Hill. Dipping roughly to the south off this core are Bunter Pebble Beds, Upper Bunter Sandstone, Keuper Sandstone and Keuper Marl.

Richardson in *Wells and Springs of Worcestershire* (1930) defines the Salwarpe as rising at Heanor on the south side of Beacon Hill. From Beacon Hill it flows through a narrow valley until it reaches Wildmoor village where it meets a tributary stream rising at Barnes Close on the south side of Windmill–Waseley Hill. This tributary stream possesses a wider valley than that of the Salwarpe itself. This valley was selected for an auger traverse (see Fig. 2).

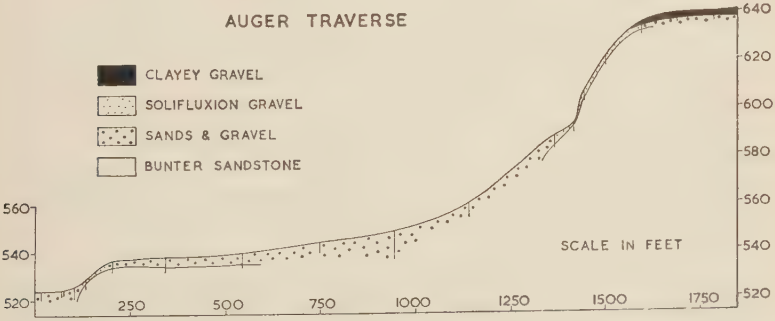

Fig. 2

The auger revealed Drifts at three different levels. The upper deposits covered the ridge top while the lower two were valley terraces. Further mapping substantiated these observations. Thus the areas occupying the hill slope of the Clent–Lickey ridge and the tops of the spurs extending therefrom were found to be covered by Drifts similar to those found in the top level of the auger traverse. These Drifts of high level clearly antedate the valleys of the Salwarpe, Hoo and their tributaries and must therefore be older than the valley terrace deposits. To distinguish the high-level drifts the name 'Older Drifts' will be used while the valley terrace deposits will be described as 'Newer Drifts'.

The Older Drifts comprise a series of sand and gravel deposits and an overlying boulder clay. It is possible to distinguish three separate members within the gravels. The Newer Drifts have been recognised in various valleys at five separate terrace levels. The full sequence of Pleistocene deposits is therefore as follows:

NEWER DRIFTS
- Alluvium
- Flood-Plain Terrace of Upper Salwarpe
- Wildmoor Terrace
- Catshill Terrace
- Marlbrook Terrace
- Bellevue Terrace

OLDER DRIFTS
- Boulder Clay
- Clayey Gravels
- Coarse Gravels
- False Bedded Sands and Fine Gravels

(a) Older Drifts

(*i*) *False-Bedded Sands and Fine Gravels.* These are the basal members of the drift sequence in the area and they are associated with deep channels cut in the sub-drift surface. They consist of over forty feet of a series of interbedded sands, pebbly sands and fine gravels, nearly always showing current-bedding. The sand is coarse and yellowish brown with a substantial proportion of heavy mineral grains and occasional carbonaceous fragments among the quartz grains. The fine gravels are composed of pebbles rarely more than three inches in diameter, consisting chiefly of Bunter types (with rounded quartzite, quartz-tourmaline rock and sandstone). A large proportion of these show angular fractures. Non-Bunter erratics may be collected in quantity by diligent searching and comprise sandstones, shales, coal fragments, Wrekin type volcanics and some far-travelled Welsh lavas and ashes.

The major exposures of these beds are seen at Money Lane (962768), Madley Heath (956772), Barnt Green Gravel Pits (985733), Blackwell Golf Club House (995721) and Cobley (007712). At Money Lane Gravel Pit, thirty-five feet of false-bedded sands and fine gravels are seen to fill a valley cut in the Upper Bunter Sandstone. Both sides of this channel are visible though the base is not exposed. At the top these beds pass rapidly into the coarse gravels described later. This pit is described and discussed by Wills (1950, 119) but at the time he wrote the two walls of the channel were not apparent. An exposure in the same deposits occurs on the other side of the road at Madley Heath Farm Pit. This pit is 250 yards to the west of Money Lane Pit and it is evident that the sands and gravels are resting in the same sub-drift channel.

False-bedded sands and fine gravels also deposited in a sub-drift channel are seen two and three-quarter miles to the south-east in sand and gravel pits at Barnt Green. These are the Combe Hill Pits worked by the Sheply Sand and Gravel Company at Brookhouse Road. Here two large worked pits reveal the west side of a channel beneath the gravels while a disused pit 200 yards to the south-east reveals the eastern side of the same channel. The two former pits display the Bunter Sandstone surface covered with a few feet of solifluxion gravel sloping down under increasing thicknesses of gravel. A maximum of forty-five feet of false-bedded sand and gravel is seen but here again the base is not exposed.

The chief difference from Money Lane is the appearance of a band of varying pebbly clay and sandy gravel within the current-bedded sands and fine gravels. This band has a visible maximum thickness of five and a half feet. It thins and disappears on approaching the sides of the buried channel and bifurcates towards the centre. The bulk is a red silty sand with a high proportion of pebbles. The pebbles are derived Bunter pebbles with other erratics of the usual type and are distributed either as discrete pebbles or in strings. In this silty sand with pebbles are lenses of sandy clay with a much lower content of pebbles. These bands of pebbly clay together with the banding in the silty sand reveal contortions which range over a vertical distance of up to a foot and are continued throughout the length of the sandy clay gravel band. This band contains numerous carbonaceous fragments both in the clay lenses and in the pebbly sand. Investigation by Frey's method of pollen analysis failed to reveal any trace of pollen in the carbon-rich areas. The long axes of the pebbles in both the sandy and the clayey parts of the band showed a random orientation.

In the south-west corner of this sand-pit the sands and gravel display festooning. At two adjacent levels gravel pushes up irregularly for some fifteen inches into overlying sand. The two levels are separated by a band of reddish sandy clay, the base of which is not disturbed. It seems that there were two periods during which the festooning took place and that the sandy clay was deposited in the interval between them. Thus the earlier period must certainly be contemporaneous with the current-bedded sands and gravels. The date of the second period is less certain owing to erosion having left these upper festooned beds at the top of the Older Drifts sequence at this point, and beneath sands and carbonaceous deposits of more recent age. However, there is little reason to suppose that it was not also contemporaneous with the current-bedded sands and gravels.

False-bedded sands and fine gravels are also exposed in the grounds of Blackwell Golf Club House and in the banks of the adjacent railway-cutting. Here again the relations show that these beds are resting in a sub-Older Drift channel but in the absence of large gravel pits, no more than ten feet of these beds can be seen in any place.

The sands and fine gravels display current-bedding demonstrating deposition by water. The fine gravels contain erratics of Welsh type and it must be presumed that they were either derived from an earlier deposited boulder clay or direct from a glacier. There is no evidence of the former and since the gravels were eventually covered by ice, depositing the boulder clay, it must be presumed that the erratics were indeed derived directly from a glacier. The false-bedded sands and fine gravels must have been deposited by glacial melt-waters flowing through the sub-drift channels. Evidence of frost action is seen in the festooning at Barnt Green.

(*ii*) *Coarse Gravels*. The false-bedded sands and fine gravels rapidly pass up into a series of coarse gravels. The buried channels previously mentioned are entrenched in a sub-drift surface of small relief and the coarse gravels not only complete the filling of the channels but also extend over the adjacent flatter surface. These gravels have a yellow-brown sandy matrix and a high concentration of pebbles, which range from less than an inch up to boulders of a foot or more in diameter. The sorting is extremely poor and only slight traces of bedding are discernible. The pebbles are largely Bunter and with the same types of other erratics as in the underlying false-bedded series.

Both at Money Lane and Barnt Green Gravel Pits some twenty-five feet of coarse gravels are present. An interesting feature in the Madley Heath Farm Pit is the appearance of a boulder bed at the base of the coarse gravels. This bed, exposed over a length of at least twelve feet, is composed of a single layer of boulders nine to eighteen inches in diameter. It contains derived Bunter Quartzites, angular sandstones (probably Coal Measures) and yielded one specimen of a felsitic igneous rock.

Mapping has proved the existence of an extensive spread of the gravel deposits across the southern flanks of the Clent–Lickey Hills. They can be traced as a nearly continuous sheet from 800 feet O.D. down to 600 feet at Wildmoor and down to 550 feet at Barnt Green. In places they contain lenses of finer gravel sometimes showing false bedding. The Wildmoor Sand Pits (955764) and the Bellevue Sand Pit (973746) show the presence of shallow pre-drift channels cut into the Bunter Sandstone. The largest of these, at Wildmoor, measures ten feet deep by fifteen feet wide, while at

Bellevue there are two channels of eight to nine feet deep separated from each other by a distance of seventy feet. The base of each of the Bellevue channels contains three feet of clayey gravel very different from the normal development of this series. The relation of these shallow channels crossing the flat sub-Older Drift surface to the major channels at Money Lane, Barnt Green and Cobley is uncertain. A theory of glacial overflow will be advanced for the major channels but these, Wildmoor–Bellevue channels, are of a very different order of size and may not have originated in the same way.

The deposit of coarse gravels above the false-bedded sands and fine gravels denotes a change in the conditions. The paucity of the bedding, the poor sorting of the pebble content and the increase of pebble size all suggest much more rapid accumulation. Now these coarse gravels are the deposits on the flattish area bordering the deep channels and the evidence bearing on the rate of accumulation indicates that the waters which deposited them must have been flowing faster across the broad land area than when they were confined to the restricted channels. Evidence of the greater transporting power of the waters is shown most strikingly by the occurrence of the boulder bed at Upper Madley Heath Farm Pit. It is suggested that the increasing coarseness of the gravel deposits was associated with melt-waters from a rapidly advancing glacier.

(*iii*) *Clayey Gravel.* Gravel deposits of a very variable nature are found capping the ridge running from the Wildmoor Sand Pits past Money Lane Gravel Pit and on to Chapman's Hill (965778). These vary from a clayey gravel to a silty or a fine sandy gravel. They apparently form a continuous sheet overlying the coarse gravels.

In the Wildmoor Sand Pit the silty gravel rests upon the coarse gravels and shows a maximum thickness of fourteen feet. It consists of a sandy silt with a few derived Bunter pebbles and occasional boulders of local Carboniferous sandstone up to one foot in diameter. The deposit shows no trace of stratification.

North-westwards along this ridge some two feet of sandy gravel with clay patches were encountered in the auger traverse (Fig. 2). Further north-west an exposure in the top of the Money Lane Gravel Pit shows two feet of silty gravel with Bunter pebbles up to six inches in diameter. The base of this deposit shows cryoturbation. This involves streaks of up to three feet of silty gravel tapering down into the coarse unstratified gravel. Similar disturbance of these gravels has not been found elsewhere in the area, and in any case it is unlikely to be of contemporary origin. Traces of sandy clay and red silty gravel are found further along the ridge revealing the extension of this variable deposit up to Chapman's Hill.

The lithological difference between the clayey gravel and the underlying gravels denotes a change in the conditions of deposition. Although there is an appreciable clay content it is doubtful if the clayey gravel can be regarded as the product of deposition by ice. It seems more likely that it can be regarded as being an outwash gravel incorporating clayey material.

(*iv*) *Boulder Clay*. Boulder clay overlies the gravel deposits and forms a continuous sheet in the area around Barnt Green, Linthurst and Blackwell Station. This sheet, of up to fifty feet in thickness, consists of a grey sandy clay containing scattered Bunter pebbles and erratics of Welsh igneous rocks. At Linthurst Clay Pit (995725) a thickness of forty feet of boulder clay was once worked for bricks. The top six feet of the section here reveals an interbedding of pebbly clay and pebbly sand lenses; otherwise the boulder clay reveals no trace of stratification. The boulder clay is underlain by only six feet of red pebbly sand above the Bunter Sandstone.

This boulder clay extends northwards as a discontinuous sheet and is found at 850 feet on Lickey Hill, at 900 feet on Beacon and Romsley Hills. It seems evident that ice capped the eastern end of the Clent–Lickey ridge but in view of the fact that neither glacial deposits nor glacial erratics are found on the tops of Clent and Walton Hills it would seem unlikely that ice capped the west end of the ridge. This indicates that while the 850 to 950 feet eastern end was submerged by ice, the 1000 feet western end existed as a nunatak above the ice surface.

The erratics in the boulder clay denotes that the ice came from North Wales. To find a direction of ice advance across the area an examination was made to determine the orientation of pebble long axes in the boulder clay at Linthurst and Barnt Green. Only pebbles below a depth of four and a half feet at the former and below a depth of six feet at the latter were used in the hope of avoiding measurements on pebbles disturbed by solifluxion. However, in both cases the preferred orientation was in agreement with the maximum slope of the ground surface and seems to be the result of downhill creep.

(b) Newer Drifts

The lowest drift level in the auger traverse at Wildmoor occupied the valley floor while the middle level was separated from the other two by steep slopes along which the solid was either exposed or covered by only a few feet of gravel clearly the result of solifluxion (Fig. 2). The composition and attitude of the two lower deposits conform to the accepted idea of river terraces. The valley floor, or flood-plain terrace, and the higher terrace, or Wildmoor Terrace, can be traced downstream to Upton Warren. A higher terrace, Catshill Terrace, is first recognised at Lower Catshill and from this point downstream it is well developed. Two even higher terraces are visible around Marlbrook (973743) where gravel occurs on two well-defined flats separated from each other and from the Older Drift by steep solifluxion covered slopes. These are the Bellevue and Marlbrook Terraces.

(*i*) *Bellevue Terrace*. Near Bellevue Sand Pit, the Bellevue Terrace shows a red clayey and pebbly sand while a quarter of a mile southwards at Staple Hill (971734), it varies from a very coarse sandy gravel to a mottled sandy gravel with clay. The tops of these two spreads are approximately fifty feet below the base of the Older Drift. A small patch of pebbly sand on the opposite side of the valley, at The Mount (950746), shows similar relations and probably represents the same terrace.

(*ii*) *Marlbrook Terrace*. At Lower Marlbrook another spread of gravel is recognisable at twenty-five feet below the Bellevue Terrace. This consists of at least six feet of an extremely coarse, poorly sorted gravel containing Bunter pebbles and angular fragments of Welsh igneous rocks. A builder's trench cut through this terrace revealed a coarse, slightly clayey gravel passing into a clayey gravel. There is no trace of bedding in either of these exposures. The pebbles show very poor sorting with large boulders of Bunter origin up to one foot in diameter mixed with very small pebbles. These gravels appear to be the product of very rapid accumulation. Apparently related to these Lower Marlbrook gravels are certain gravel-covered benches occurring both upstream and on the opposite side of the valley.

(*iii*) *Catshill Terrace*. This consists of a coarse sandy Bunter pebble gravel covering extensive flat areas around Upper Catshill. A gravel pit marked on O.S. maps at Upper Catshill is sited on this terrace. Since the solid rock here is pebble-free Bunter Sandstone, the pit must have worked the terrace gravels but no exposures are available at this point. Remains of this terrace extend downstream through Bromsgrove and include the gravel-covered flat area known as Stoke Heath. The magnitude of the erosion in the period between the deposition of the Older Drifts and the formation of the Catshill Terrace is shown by the fact that the terrace floors a valley originally half a mile wide and cut 130 feet below the Older Drifts.

(*iv*) *Wildmoor Terrace*. The Terrace at Wildmoor consists of a series of coarse gravels resting upon coarse sand with some angular sedimentary fragments and rare small derived Bunter pebbles. The maximum thickness proved by augering was ten feet of coarse gravels on at least two feet of sand with rare pebbles. At Wildmoor the base of the terrace is only twelve feet above the top of the Salwarpe Flood-Plain. It is separated from the latter by a short steep slope along which the solid rock is covered by a foot of solifluxion gravel. Traces of this terrace are found downstream, the base of the terrace increasing its height above the flood-plain terrace to twenty feet at Stoke Prior.

(*v*) *Upper Salwarpe Flood-Plain Terrace*. At Wildmoor the Flood-Plain Terrace is an extremely coarse Bunter pebble gravel which proved impossible to auger. Exposures of sandy gravel with erratics of Welsh igneous rocks were found downstream. At Upton Warren a gravel quarry excavated in this terrace has revealed twenty-five feet of sandy and clayey gravel with fossil-bearing dirt-bands.[1] The Flood-Plain Terrace attains a width of 1500 feet within only one and a quarter mile of the source of the river. Its width downstream varies but eventually becomes 3000 feet at Upton Warren. At Whitford Mill (947706) the river begins to cut through the terrace gravels until at Wychbold (923664) the Upper Salwarpe Flood-Plain Terrace becomes a valley side terrace above a flood-plain terrace of more recent age.

The River Salwarpe is of negligible dimensions along the upper part of the valley and at Bromsgrove is still only six feet wide by three to four feet deep. This size of stream is incapable of accomplishing the amount of erosion necessary to produce the terraces. The Salwarpe must have been considerably larger when the terraces were cut and may have owed its increased size either to greatly increased rainfall or to the rapid melting of a snow cover accumulating on the Clent–Lickey ridge, or to both causes.

The Hoo Brook, rising on Romsley Hill and flowing to the west of the Salwarpe, also shows well-developed gravel terraces which it would be premature to correlate with those of the Salwarpe. Three can be recognised in the upper part of the valley. The lower one is cut through at Bell Heath (953774), where the stream flows through a small gorge known locally as 'The Gutter'. Other gravel terraces can be recognised in streams tributary to the Salwarpe such as the Spadesbourne Brook. Although they have not been mapped in detail they are clearly representatives of the terraces in the main part of the Salwarpe Valley.

The slopes between the terraces both in the Salwarpe and Hoo Brook Valleys are covered with solifluxion deposits. The amount varies from one to three feet but increases up to ten feet in the bottoms of gulleys cut into the slopes. These deposits fan out from the base of the gulleys and merge into the lower terrace deposits.

Drift deposits filling a channel cut into Older Drift gravel are found in the south-west corner of the main Barnt Green gravel pit. This channel is approximately twenty-five feet wide by four feet deep. The basal deposits consist of pinkish-yellow clayey sand irregularly mottled and penetrated by a few roots, and these pass upward into grey sand. Above these are sands rich in carbonaceous matter which reach a maximum of two feet thick. The channel yields pollen indicative of temperate conditions.

The channel is covered by three and a half feet of pebbly sand which, lying on an irregular, disturbed surface of the top of the channel, is interpreted as due to solifluxion down the present hill-slope. Until work now being done on the pollen content of the channel indicates whether it is interglacial or post-glacial, it is not possible to put a lower date to the solifluxion.

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[1] The fauna and flora of this quarry is being investigated at Birmingham University.

3. CORRELATION OF DRIFT DEPOSITS

The erratic content of the boulder clay suggests that the associated ice was derived from North Wales. Now since only the First and Second Welsh ice advances are known to have reached the Clent–Lickey area, then the boulder clay must be assigned to one of these two glaciations. In surrounding areas the deposits of the First Welsh ice are infrequent and scattered while those of the Second Welsh form thick and extensive sheets. As only one till has been found on the south side of the Clent–Lickey Hills and it forms a fairly thick and extensive sheet, it seems certain that it must be due to the Second of the two Welsh glaciations and so be equivalent to the Riss glaciation (Shotton, 1953). The underlying gravels most probably represent the outwash gravels of the advancing Second Welsh glacier.

Correlation of the Newer Drift terrace gravels was effected by mapping, levelling and constructing a longitudinal profile of the valley so as to demonstrate their relations to the terraces mapped by Reeves along the lower part of the Salwarpe. Reeves's terraces have been correlated with those established in the Severn Valley by Wills (1938).

Wills gave a sequence of six terraces. His highest was the Woolridge Terrace which he correlated with the stage of First Welsh glaciation. The next terrace below, the Bushley Green Terrace, was correlated with Avon No. 5 Terrace and also considered to antedate the Second Welsh glaciation. These two views are incompatible, for in the Avon Valley Terrace No. 5 is clearly later than the Second Welsh glaciation. Furthermore, in order to pond Lake Harrison to the necessary 410 feet (or 435 feet as suggested by Bishop, 1958) ice of the Second Welsh glacier must have extended down the Severn Valley and occupied the area between the Ridgeway and Cleeve Hill. Had the Bushley Green Terrace existed before this extension of the ice then it would be unlikely to have retained its river terrace form while being over-run by ice. Yet the Bushley Green Terrace does not show the effects of erosion by moving ice, nor is it capped by till. It appears likely therefore that this terrace was formed during a retreat stage of the Second Welsh glaciation concurrently with No. 5 Terrace of the Avon and this is the view put forward in Bishop (1958) and held by Shotton. It is also the view of Hey (1958). If this is correct then there are five terraces in the Severn Valley which postdate the maximum of the Second Welsh glaciation.

On the gradient diagram (Fig. 3) the river terraces of the Upper Salwarpe have been plotted, as well as the extension of the Severn Terraces up the Lower Salwarpe mapped by Reeves, that is the Main Terrace up to Upton Warren and the Kidderminster Terrace at Wychbold. The flood-plain terrace of the Upper Salwarpe is seen to make a smooth curve from 700 feet at Barnes Close down to 170 feet at Upton Warren. Now this terrace at Upton Warren is also that which Reeves considered to be the Salwarpe continuation of the Main Terrace of the Severn. This view has been

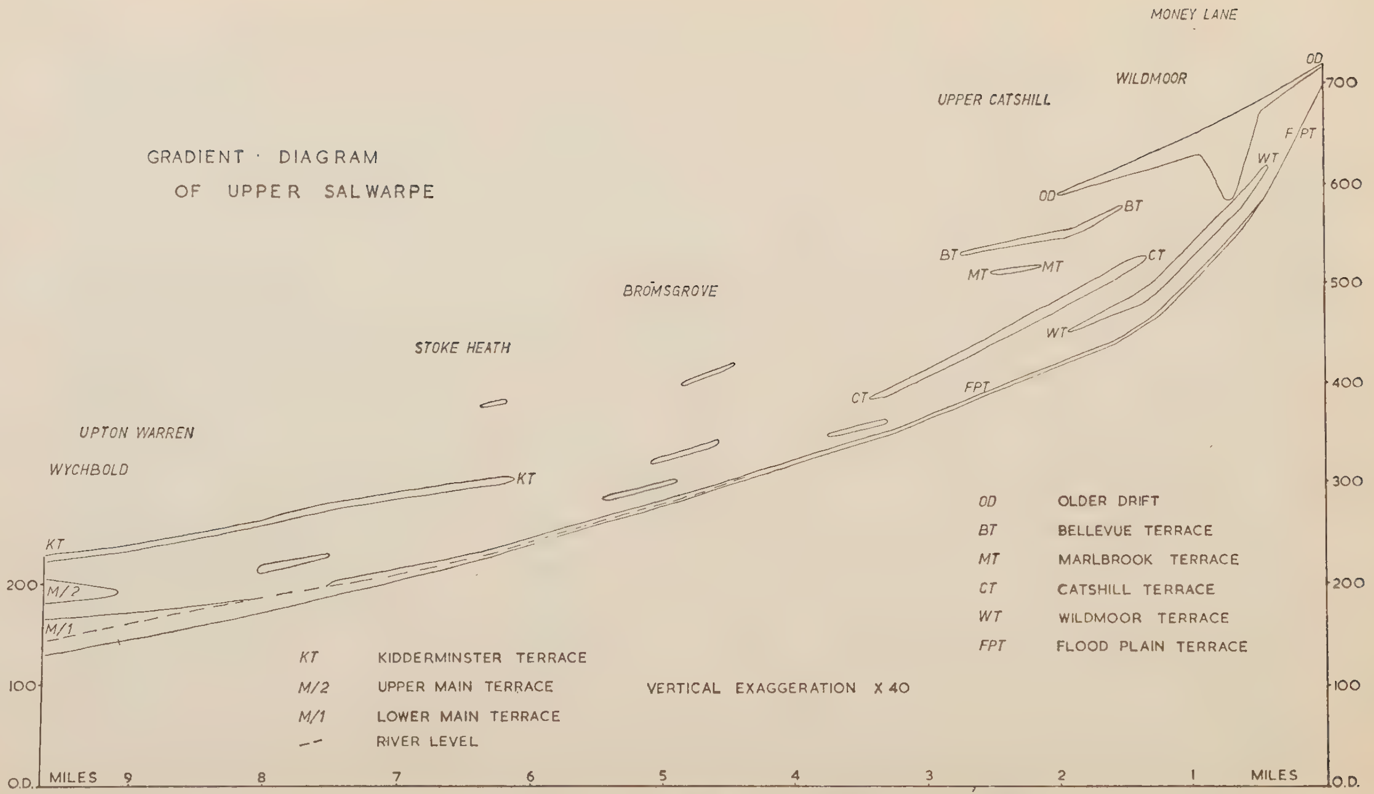

GRADIENT · DIAGRAM
OF UPPER SALWARPE
MONEY LANE
WILDMOOR
UPPER CATSHILL
BROMSGROVE
STOKE HEATH
UPTON WARREN
WYCHBOLD
OD
F/PT
WT
OD
BT
BT
CT
MT
MT
WT
CT
FPT
KT
KT
M/2
M/1
OD OLDER DRIFT
BT BELLEVUE TERRACE
MT MARLBROOK TERRACE
CT CATSHILL TERRACE
WT WILDMOOR TERRACE
FPT FLOOD PLAIN TERRACE
KT KIDDERMINSTER TERRACE
M/2 UPPER MAIN TERRACE
M/1 LOWER MAIN TERRACE
-- RIVER LEVEL
VERTICAL EXAGGERATION X 40
O.D.
100
200
300
400
500
600
700
MILES
9
8
7
6
5
4
3
2
1
MILES

Fig. 3

supported by examination of the fauna found at Upton Warren. This establishes not only a dating for the Upper Salwarpe Flood-Plain Terrace but implies limiting dates for the higher level terraces of the Upper Salwarpe.

Wills established two levels for the Main Terrace—an M/2 above an M/1 level. M/2 was recognised near the confluence of the Severn and Salwarpe at Hawford Grange while M/1 was recognised nearer the river. An intermediate bench between the Kidderminster and Lower Main Terrace levels is prominent at Wychbold and a recent boring through this shows the existence of at least twenty feet of clayey gravel resting upon Keuper Marl. This gravel terrace must represent the M/2 level. The gradient diagram shows that it continues upstream and becomes represented by the Wildmoor Terrace. In this connection it must be remembered that Wills considered the deposits of M/2 to be younger than M/1. The auger traverse at Wildmoor showed the existence of a rock step between the Wildmoor and Flood-Plain Terrace and indicated that the former is older than the latter. If this correlation is correct, then the Wills's theory of the M/1–M/2 relation does not apply to the Salwarpe Valley.

The Kidderminster Terrace at Wychbold is evidently the same terrace as that forming Stoke Heath and the profile suggests that it is represented by the Upper Catshill Terrace. Any alternative correlation leaves the Wildmoor Terrace of the Upper Salwarpe and the Kidderminster Terrace of the lower valley without obvious correlatives. It therefore follows that the Marlbrook and Bellevue Terraces must represent the period between the Second Welsh maximum and the Kidderminster Terrace, and so must be broadly equivalent to the Bushley Green Terrace. Wills has stated that there is more than one level represented by the latter so the presence of two terraces in the Upper Salwarpe need not be regarded as unusual. A correlation of the Drift deposits in the Upper Salwarpe and Severn Valleys may then be drawn up as follows:

UPPER SALWARPE	SEVERN
Alluvium	Alluvium and Worcester Terrace
Flood-Plain Terrace	Main Terrace (M/1 level)
Wildmoor Terrace	Main Terrace (M/2 level)
Catshill Terrace	Kidderminster Terrace
Marlbrook Terrace Bellevue Terrace	Bushley Green Terrace
Boulder Clay Gravel Deposits	Second Welsh Glaciation

4. THE SUB-OLDER DRIFT CHANNEL

Reference has been made earlier to the occurrence of the lower part of the gravel sequence in a steep-sided channel—a most striking and anomalous feature of the sub-Drift topography. Such a channel is visible from

Madley Heath to Money Lane for a distance of half a mile. Another and similar channel is traceable continuously from Barnt Green to Cobley over a distance of three and a half miles. Between these two lengths lies the lower ground of the Salwarpe Valley, cut down and occupied by terraces at a lower level. Two possibilities suggest themselves:

(a) Both channels are relics of one continuous channel from Madley Heath to Cobley.

(b) That at the time of formation a river valley occupied the ground between the two channels.

Fig. 4 shows the first view in a reconstruction of contours which satisfies all the known occurrences of the gravels and does not conflict with the present levels of the intervening valley. The contours indicate that the channel had the form of either a very deep V or a U shape. At Money Lane this channel is about 300 feet wide and the total depth revealed in the pits is 60 feet but it is obviously deeper than this. A similar order of size exists at Barnt Green. The inclination is from north-west to south-east, the base being just under 550 feet at Money Lane but below 500 feet at Barnt Green and Cobley.

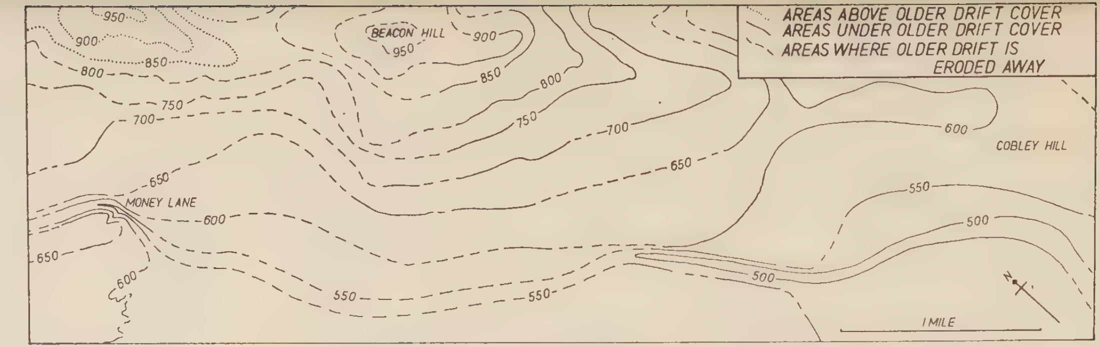
The channel is aligned roughly parallel to the orientation of the Clent–Lickey–Ridgeway watershed and at right angles to the slope of the regional drainage. In view of this it appears improbable that the channel could have been excavated by normal stream erosion across a pre-Older Drift surface. At the time of formation drainage from the watershed towards the south and west must have been prevented by a glacier—the channel being excavated as a marginal channel against an ice front. The ice could have been an extension of the Severn Valley ice advancing round the west end of the Clent Hills and butting up against the south slope of the Clent–Lickey Ridge.

Water capable of cutting this deep valley could have had one or both of the following sources:

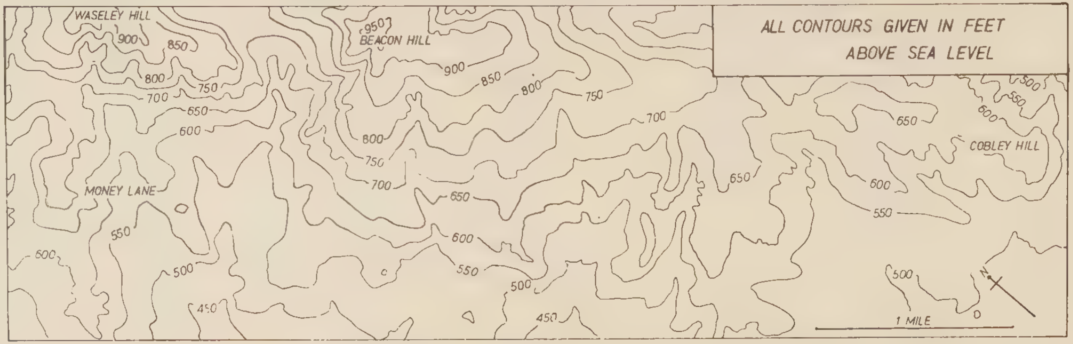
(a) A lake in the region of the Hoo and Elmley Brook Valleys.

(b) A lake north of the Clent–Lickey Ridge, impounded by ice advancing from the Birmingham direction, and overflowing through the wide flat-bottomed col which exists between Clent and Walton Hills and reaching the Madley Heath–Cobley channel via the lake postulated in (a).

The channel grades down from north-west to south-east and turns parallel to the Ridgeway. It does not cross the Ridgeway, the latter forming a solid barrier of Keuper Marl unbreached by drift. If the Severn Valley ice had advanced to the east side of what is now the Salwarpe Valley the overflow drainage could have run between the ice front and the crest of the Ridgeway.


AREAS ABOVE OLDER DRIFT COVER
AREAS UNDER OLDER DRIFT COVER
AREAS WHERE OLDER DRIFT IS ERODED AWAY
BEACON HILL
COBLEY HILL
MONEY LANE
950
900
850
800
750
700
650
600
550
500
N
1 MILE

CONTOURS ON THE SUB-OLDER DRIFT SURFACE



PRESENT DAY CONTOURS

Fig. 4

The next step is to elucidate the age of these channels. The following points are relevant to this problem.

(i) It is unlikely that the ponding of the waters involved a medium other than ice and therefore the cutting of the channel probably dates from one of the glacial stages.

(ii) Outwash gravels and a boulder clay of Second Welsh age were deposited after the channel was cut: so the channel must have originated either during Second Welsh times or before.

(iii) If the channel was cut during First Welsh times it had to pass through the Great Interglacial Period and retain its steep-sided form until burial by deposits of the Second Welsh Glaciation. It is unlikely that it could have passed through the Great Interglacial without some erosion of the steep sides.

(iv) Deposits definitely referable to First Welsh or Great Interglacial times have not been observed in the channel.

The evidence strongly favours formation of the deposits in Second Welsh times.

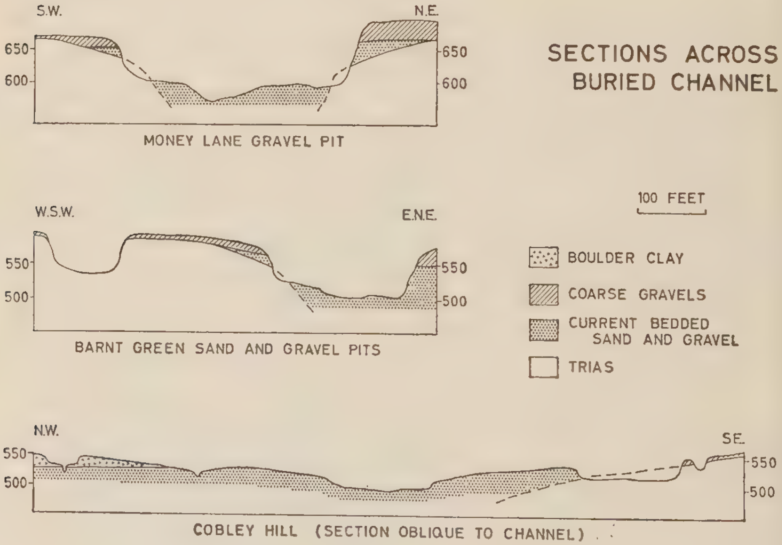

S.W.
N.E.
650
600
650
600
SECTIONS ACROSS BURIED CHANNEL
MONEY LANE GRAVEL PIT
W.S.W.
E.N.E.
550
500
550
500
100 FEET
BOULDER CLAY
COARSE GRAVELS
CURRENT BEDDED SAND AND GRAVEL
TRIAS
BARNT GREEN SAND AND GRAVEL PITS
N.W.
SE.
550
500
550
500
COBLEY HILL (SECTION OBLIQUE TO CHANNEL)

Fig. 5

The outwash gravels of the Second Welsh glacier represented by the overlying till fill not only the channel but spread on to the flatter sub-drift surface and have been mapped for nearly half a mile south-west of the line of the channel. Thus between the cutting of the channel and the final till there must have been a retreat of the ice to enable the outwash gravels to be deposited. Since reasons have been offered against this earlier glacial maximum being First Welsh then it is suggested that the channel and its outwash gravels represent two oscillations of the Second Welsh ice front.

ACKNOWLEDGMENTS

I am very grateful to Professor Shotton for supervising the research described in this paper and for much helpful advice and assistance in the field, and to Professor Wills who not merely discussed my problems, but also placed his field maps and notebooks at my disposal. I would also like to thank all those who have kindly helped me with augering and levelling.

REFERENCES

BISHOP, W. W. 1958. The Geomorphology and Pleistocene Geology of Three Gaps in the Midland Jurassic Escarpment. *Phil. Trans.* B, **241**.

BRITISH ASSOCIATION REPORT. 1875. Erratic Blocks Committee. Report on Bromsgrove District.

———. 1878. Further Report on Bromsgrove District.

CROSSKEY, H. W. 1888. Notes on the Glacial Geology of the Midlands. *Proc. Bgham. nat. Hist. Soc.*

HEY, R. W. 1958. High Level Gravels in and near the Lower Severn Valley. *Geol. Mag.*, **95**.

PICKERING, R. 1957. The Pleistocene Geology of the South Birmingham Area. *Quart. J. geol. Soc. Lond.*, **113**.

RICHARDSON, L. 1930. Wells and Springs of Worcestershire. *Mem. geol. Surv. U.K.*

SHOTTON, F. W. 1953. The Pleistocene Deposits of the Area between Coventry, Rugby and Leamington and their bearing upon the Topographic Development of the Midlands. *Phil Trans.* B, **237**.

STRICKLAND, H. E. 1842. Memoir Descriptive of a Series of Coloured Sections on the Cutting of the Birmingham and Gloucester Railway. *Trans. geol. Soc., Lond.*, 2nd Series, **6**.

WILLS, L. J. 1937. The Pleistocene History of the West Midlands. *Advanc. Sci.*, Nottingham, 1937.

———. 1938. The Pleistocene Development of the Severn from Bridgnorth to the Sea. *Quart. J. geol. Soc., Lond.*, **94**.

———. 1950. *Palaeogeography of the Midlands.* 2nd Edition. Liverpool.

Strand-line Pebbles in the mid-Hastings Beds and the Geology of the London Uplands. General Features. Jurassic Pebbles

by P. ALLEN

With an Appendix on the derived Jurassic Ammonites
by the late Dr. W. J. Arkell

Received 22 September 1958

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ABSTRACT: Evidence is presented supporting earlier suggestions that the detritus carried to the Wealden basin by the 'northern river' consisted mainly of waste from Upper Jurassic, Lower Carboniferous and Old Red Sandstone strata, and that this reflects the changing stratigraphical succession exposed by denudation in the London area during the deposition of the Hastings Beds. The Upper Jurassic contribution is described in detail.[1]

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1. INTRODUCTION

A PRELIMINARY ATTEMPT has already been made to map the solid geology of the London Uplands as they existed during Wealden times (Allen, 1954). The report stressed the importance of the evidence provided by the graded pebble beds capping the Ashdown, Lower Tunbridge Wells and subsidiary arenaceous formations. These pebble beds are basal conglomerates, marking the beginnings of major transgressions which resulted in the deposition of overlying clay formations (Wadhurst and Grinstead). They are beach deposits: strand-line gravels spread over extensive areas by the northward-retreating coastlines of the Ashdown and Lower Tunbridge Wells deltas (Allen, 1959; 1960). As the rising lake-waters drowned the lower reaches of the distributaries the levees crumbled away, freeing the pebbles to spread wider afield under the influence of more open water currents.

Nearly all the pebbles in the conglomerates seem to have originated in the London Uplands. They were brought southwards in the short, steep 'northern river', the main pass or 'head of passes' of which usually lay somewhere in the longitude of West Wickham (Allen, 1954, 504). Petrological study should therefore give a broad idea, though a selective one, of the more resistant formations outcropping in the catchment area. The gathering ground itself must have comprised a large area to the north of the Thames, centred roughly on what is now Metropolitan London. Since the datable pebbles are nearly all of Old Red Sandstone, Lower Carboniferous and Upper Jurassic rocks, these were presumably the chief formations outcropping in the Uplands (*cf. op. cit.*, 505–7).

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[1] Carboniferous, Old Red Sandstone and other components will be the subjects of later papers.

Subsequent work on the pebbles, to be reported in this and succeeding papers, confirms and extends these conclusions. Here, general features of the assemblages are first described; then the Jurassic components in more detail.

2. GENERAL FEATURES OF THE PEBBLE ASSEMBLAGES

(a) Sampling

At an early stage it became evident that very large random samples of coarse conglomerate would be needed. The horizon chosen for intensive work was the Top Lower Tunbridge Wells Pebble Bed, and the area within it the one-and-a-half-mile-wide tract running south from East Grinstead to Paxhill (Allen, 1954, text-fig. 1; 1959). There, the pebbles are biggest and most abundant and the bed attains its greatest thickness. The tract seems to represent a late Lower Tunbridge Wells distributary, partially obliterated by the transgressing Grinstead Lake. Two localities were selected for detailed investigation:

(1) *Paxhill Park* (356272).[1] An overgrown 'hollow' in the roadside (B2028) shaw nearly opposite the entrance to 'Buxshalls', one mile north-east of Lindfield. Three hundredweights of conglomerate were obtained. This is probably the historic locality where Topley 'found a small fragment of an *Ammonite*' (1875, 84).

(2) *Hook Quarry, West Hoathly* (355313). Six tons of conglomerate were obtained. This locality is referred to by Milner (1923, 288). (The quarries in West Hoathly have attracted geologists for many years and the pebble assemblage at Philpots, half-mile north of Hook Quarry, has previously been reported (Milner, *op. cit.;* Kirkaldy, 1947).)

The samples were transported to the laboratory by lorry, disaggregated, and pebbles more than one-quarter inch wide screened off. These were washed and examined under the hand-lens and binocular microscope. Where necessary, investigation was aided by cutting thin sections or preparing flat surfaces (polished or mounted under glass); several hundred representative types and all unrecognisable or otherwise interesting pebbles were treated in this way.

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[1] National Grid references lie in the 100 km. square 51 (TQ).

Owing to the absence of large exposures sampling of the Top Ashdown Pebble Bed (Allen, 1949a, fig. 2) was restricted to small collections from all the 300+ localities now known. Larger than normal samples were taken from two exposures at the extreme NW. and SE. limits of outcrop:

(1) *Near The Grove, Penshurst* (513429). Overgrown pit one-quarter mile down the old lane leading to Salman's Farm.

(2) *Oxenbridge Hill, Iden* (917249). West road-bank by B2082, three-fifths of a mile south-east of bridge over River Rother.

More detailed information is therefore available from these. Laboratory treatment was as before.

Comprehensive close sampling of the remaining pebble beds has so far proved impossible. Only the Telham and Cliff End Pebble (Bone-) Beds will be specifically mentioned here (see, e.g. Allen, 1949b, fig. 45; 1960, 11). The former caps the Hog Hills Sands within the Wadhurst Clay, and therefore intervenes between the Ashdown and Lower Tunbridge Wells horizons. As will be seen, neither seems to have much bearing on the problems of the London Uplands.

(b) Petrographic Types and Frequencies

All horizons show an overwhelming predominance (>99%) of siliceous pebbles containing more than 95% silica. This suggests derivation from pre-existing sediments, combined perhaps with intense or prolonged weathering and transport.

A general idea of the relative frequencies of the broad petrographic types normally present in the Top Lower Tunbridge Wells Pebble Bed was gained by analysing the three hundredweight Paxhill sample. This was first well mixed, split down to 2052 pebbles, and the frequencies determined by counting (see Table I). The values obtained, of course, are in no way estimates of the average frequencies characterising the pebble bed over its whole area. Marked fluctuations take place from one locality to another. This is sometimes seen even when there is no change in particle size: at Hook Quarry (West Hoathly), for instance, there are appreciably more phosphorites than at Paxhill. However, actual changes in the coarseness of the pebble grade are the most important causes of lateral fluctuation in composition. Phosphorite, chert and red-stained materials become commoner as pebble size increases. This is true both between and within localities, and even within single samples. Such behaviour reminds one of the 'restricted minerals' in the Wealden sand grades (Allen, 1949a). Clearly larger pebbles of phosphorite, chert and red-stained rock were in more plentiful supply at the sites of deposition than smaller ones.

Conspicuously red-stained pebbles form 4.5% of the total: in the assemblage larger than half-inch the ratio is 10.5%. These are minimum figures, for many which were unstained on their surfaces are found to possess red cores. Yet others have been completely leached of their oxide stains. Since the various stages of leaching occur jumbled together, the cause was probably not entirely a pre-Wealden one.

All the pebbles obtained from the older Top Ashdown Pebble Bed belong to petrographic types known in the Lower Tunbridge Wells horizon, excepting the green 'chert' which has not been found. They too were derived chiefly from Upper Jurassic, Lower Carboniferous and Old Red Sandstone formations. Even the more bizarre curiosities of unknown origin (e.g. orthoclase-quartz-schist) are as widely spread south-eastwards as the outcrops allow. The main differences from the younger horizon lie rather in changed frequencies: differences, of course, very difficult to assess in view of the considerable compositional fluctuations within each bed. But, whatever the coarseness of the Ashdown samples or their geographical positions relative to London and the Tunbridge Wells outcrop, they usually show (1) very much less phosphorite and red-stained material, and (2) more (mainly ?Portlandian) chert. In proportion, the phosphorites and reddened pebbles are quite negligible, and indeed often only noticeable when larger samples than usual are taken. One explanation among several is that, during the Ashdown–Grinstead interval, erosion redistributed the Upper Jurassic and widened the Old Red outcrops.

Compositional fluctuations within the top Ashdown pebble grades are difficult to handle, and it is obvious that the figures previously published (Allen, 1949a, 272) do not represent the complete picture. They would in any case be misleading if applied without qualification to problems of the London Uplands, for the Top Ashdown Pebble Bed is at least a two-inflow conglomerate (*op. cit.*). Thus quartz- and quartzite-rich detritus from the 'north-eastern river', deficient in chert and very reminiscent of that over the Kentish Coalfield (*op. cit.*, 299), becomes an important constituent in the south-eastern Weald around Wittersham, Iden, Rye and Hastings. More useful as general guides are analyses of the two random samples cited (see Table I): one from Iden at the south-eastern extremity of outcrop; one from Penshurst, in the north-west, twenty-seven miles nearer the London Uplands and lying at roughly the same distance from them as the East Grinstead–Paxhill tract. The latter, of course, was almost entirely under the aegis of the Uplands. As expected, cherts (particularly the non-Carboniferous ?Portlandian varieties) and red-stained materials are more common in the north-west, and quartz and quartzite are correspondingly more abundant in the south-east.

The Cliff End and Telham Pebble (Bone-) Beds are quite different. Quartzes and metamorphic quartzites dominate the exotic pebble suites and the few phosphorites doubtfully assigned an origin outside the basin are petrographically distinct. Indeed, both horizons contain abundant pebbles brought in by the 'north-eastern river', which in the same district 'pollutes' the Ashdown pebble bed (see above). Severely restricted to the

TABLE I

Pebbles > 0.25 ins.

Petrographic type	Per Cent			Origin
	TLTWPB*	TAPB†		
	Paxhill (356272)	Penshurst (513429)	Iden (917249)	
CHERT	59.5	86.3	73.9	Upper Jurassic and Lower Carboniferous
Miscellaneous	72.5	76.6	75.5	
Bedded, non-oolitic	18.5	16.9	23.8	
Oolitic	9.0	6.5	0.8	
(Patinated)	(59.1)	(22.3)	(23.8)	
(Red-stained)‡	(0.49)	(0.7)	(0.0)	
QUARTZITE	19.6	3.4	6.0	Mostly Old Red Sandstone. (Some direct from Lower Palaeozoic?)
White, mottled grey and white	41.0	64	70	
Miscellaneous	28.4			
Buff	7.0	+	10	
Dark (incl. subgreywacke)	6.0	18	10	
Pale siltstone	3.0	+	+	
Red-stained‡	14.7	18	10	
(Quartz-veined)	(8.0)	(+)	(20)	
QUARTZ	19.4	9.0	18.2	Mostly Old Red Sandstone
Opaque white	58.6	65.5	30	
Opaque grey and brown	25.6	24.1	40	
Translucent	7.8	6.9	23	
Aggregated with Fe–Mg minerals	1.3	+	3	
Red-stained‡	6.8	3.4	3	
(Sheared or lineated)	(2.5)	(3.4)	(+)	
ORTHOCLASE-QUARTZ-SCHIST	0.6	0.9	0.6	Unknown
GREEN 'CHERT'	0.4	0.0	0.0	Old Red Sandstone
PHOSPHORITE	0.3	+	1.2§	Upper Jurassic
ACID LAVAS, etc. (red-stained)‡	0.1	0.3	+	Old Red Sandstone
SILICIFIED WOOD	0.1	+	+	Carboniferous
(RED-STAINED)	(4.5)	(1.6)	(1.2)	(Old Red Sandstone)
Total pebbles counted	2052	322	165	

* TLTWPB = Top Lower Tunbridge Wells Pebble Bed.

† TAPB = Top Ashdown Pebble Bed.

‡ Percentages for red-stained pebbles are likely to be underestimates.

§ Overestimate for this locality.

N.B. 1. Types of pebble listed as + are present in the locality, but did not appear in the sample counted.

2. The top Lower Tunbridge Wells sample was much coarser-grained than the two from the top Ashdown.

south-eastern Weald (Allen, 1949b, fig. 45), the Telham bed clearly shows that it was merely a gravelly patch on a receding strand-line, locally pebbly because it happened there to be retreating across a major deltaic pass of the north-eastern river. Isolated geographically and sedimentologically from the northern streams, their composition can have little bearing on the constitution of the London Uplands.

3. JURASSIC PEBBLES

(a) Top Lower Tunbridge Wells Pebble Bed

(*i*) *Phosphorite*. Despite their low proportions (normally less than 1%) many thousand phosphorite pebbles were examined, chiefly from the exposures at West Hoathly (Hook and Philpots quarries) and Paxhill. Generally speaking, phosphorites are most abundant where the pebble suites are coarsest (particularly Hook Quarry), and virtually confined therefore to the degraded north–south distributary (Allen, 1954, text-fig. 1; 1959). The vast majority are dark in colour (nearly black), well rolled, and consist of almost pure collophane. Often the paler nodules demonstrably owe their colour to recent leaching by soil waters (e.g. Paxhill). Gradations to phosphatic siltstone and sandstone occur, though rarely. Impregnation with glauconite is common.

The main types yielding clues to age are rolled fragments of internal casts of ammonites, a small proportion of which occur at all three localities. The six-ton sample from Hook Quarry yielded 1485 such fragments, 224 of which were submitted to Dr. W. J. Arkell. As will be seen from his report (see Appendix), all but two are parts of perisphinctids, representing a *Pavlovia* fauna of the *rotunda* Zone of the Upper Kimeridge Clay (S3–S226[1]). Very probably they embrace the entire known ammonite fauna (five species of *Pavlovia*) of the Upper Lydite Beds. Two internal casts of camerae from Paxhill (S1, S2) were reported by Dr. Arkell as indeterminate, and since then several specimens of *Pavlovia* (S 3001–6) have been obtained from Philpots (355322).

The preservation of the derived ammonites in the lydite beds and their correlative phosphatic nodule beds is identical with that of the Wealden material, but the fragments are less rolled. Some years ago the siliceous pebble suite of the earlier (Ashdown) horizon suggested comparison with the lydite beds, carrying the implication that these might be present on the south side of the London Platform (Allen, 1949a, 272). In 1957 the Geological Survey's deep boring near Warlingham (Surrey) penetrated a nine-inch bed of phosphatised *Pavloviae*, lying at or very near the top of the Kimeridge Clay (maximum possible distance from the Portland–Kimeridge boundary: ten and a quarter feet).[1] The ammonites are preserved as dark phosphorite and, as expected, are less rolled.

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[1] Reading University Geology Department registered numbers.

Like the Upper Kimeridge phosphatic nodule beds in Dorset (Arkell, 1947, 82), but unlike the lydite beds of Buckinghamshire, Oxfordshire and Wiltshire, the Surrey horizon contains no siliceous pebbles. They may of course enter farther north. Obviously, therefore, the Lower Tunbridge Wells cherts, quartzites, etc., could have come either directly from pre-Jurassic outcrops on the London Uplands or secondarily (with the ammonites) through the Upper Kimeridge. The former possibility seems the more likely, in which case the ancient rocks were probably separated in places from the overstepping lydite beds by thin Oxfordian, for one of the non-perisphinctid fragments (S226) is identified by Dr. Arkell as ? *Kosmoceras* (*Lobokosmokeras*). The other non-perisphinctid (S225) remains unidentified.

Among the few pelecypod fragments obtained from Hook and Philpots Quarries Dr. L. R. Cox has identified *Grammatodon* sp. (S227–S230) and *Isocyprina* ?sp. (S231). Though not diagnostic of the Kimeridgian could quite possibly be of this age.

Equally rare gastropod fragments from Hook include two identified by Dr. Cox as *Amberleya* ?sp. (S237 and S238). These resemble the Corallian species usually identified as *Littorina muricata* (J. Sow.).

Highly rolled pebbles with no semblance of organic shape constitute most of the phosphorite suite and grade imperceptibly into those of recognisable molluscan form. Like the molluscan casts they are normally almost devoid of detrital matter, but sometimes contain shell chips (e.g. S253 and S254) to fine phosphatic glauconitic sandstones (S255). Professor Alan Wood reports that only the long-ranged foraminiferan genus *Glomospira* is identifiable (S253, from Paxhill), and Dr. R. H. Cummings inclines to the view that the specimen in question is not Upper Palaeozoic. The same applies to another (unidentifiable) foraminifer from Paxhill (S254), which Dr. Cummings considers unlikely to be Upper Palaeozoic and Professor Wood places as more probably Mesozoic than Palaeozoic.

(*ii*) *Cherts.* Unstained (not red) cherts, mostly replacing limestones of almost every conceivable kind, commonly form at least half of the large pebbles more than one-quarter inch wide. The non-Carboniferous types are usually unfossiliferous, brittle and black, or else patinated to a soft 'white chalky looking stuff' (Topley, 1875, 84). As originally suggested by Topley and confirmed by Relf (1916, 300) and Milner (1923, 298), they may be Portlandian in age, and their petrography is consistent with this. Ooliths, if present, frequently patinate before the matrix, showing up as white 'flour'-filled pock-marks on a dark ground. The dark brittle and soft floury cherts at Paxhill have yielded fragments of a silicified terebratulid (S256); also crinoid stems (S258) compared by Dr. L. Bairstow with *Balanocrinus*, a genus ranging from Trias to Eocene. These pebbles are almost certainly Jurassic. There is little possibility of confusing Jurassic with Lower Carboniferous chert: the pebbles of the latter are brown-mottled, grey, or white in colour, less brittle, more rounded, and tough and hard even when patinated. If ooliths are present in the Carboniferous cherts, then they either wear flush with the surface or stand out in relief.

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[1] Information communicated by the Director, Geological Survey of Great Britain, and published with his permission.

(*iii*) *Limestone*. Milner (1923, 288, 298) records pebbles of oolitic limestone from the East Grinstead district and figures a thin section of one from Philpots Quarry (pl. 21A). By implication he suggests a Portlandian age for it on petrological grounds (p. 298).

(b) Top Ashdown Pebble Bed

Mention has been made of an earlier comparison (Allen, 1949a, 272) between this and the Upper Lydite Bed pebble suite, drawn prior to the discovery of derived Pavlovids in the Hastings strata.

(*i*) *Phosphorite*. This material is much rarer than in the Top Lower Tunbridge Wells horizon. Consequently, owing to the impossibility of collecting bulk samples, far less is known about it and none of the forms is identifiable. The petrography is identical with that in the higher bed (e.g. S259), showing frequent glauconite impregnation and the same variations from pure collophane to argillaceous and sandy phosphorite. Almost certainly the pebbles came from a similar Upper Jurassic source.

(*ii*) *Chert*. Pebbles of chert, distinct from their Lower Carboniferous associates, often patinating to soft white 'flour' and petrographically identical with those of presumed Portlandian age in the Tunbridge Wells bed, are locally abundant. Normally indeed they are commoner than at the higher horizon. One petrographic variety (S260) from Hoathly Farm, Lamberhurst (656367), has, unlike its Lower Tunbridge Wells counterparts, yielded a possible foraminifer, compared by Mr. A. G. Davis to *Agathammina* and considered by Professor Alan Wood and Dr. R. H. Cummings as more likely non-Carboniferous than Carboniferous.

Several pebbles of monaxon spicular chert from Hurst Green (722287), though probably Lower Carboniferous on general grounds, are extraordinarily similar to certain Purbeckian sponge-cherts. This recalls the record of a chert pebble with *Spongilla purbeckensis* in it from the Lower Greensand of West Malling (Kirkaldy, 1947, 235). The problem will be discussed more fully in a later paper dealing with the Lower Carboniferous cherts.

3. CONCLUSIONS

Upper Jurassic strata about the level of the lydite beds (Upper Kimeridge to basal Portlandian) outcropped extensively in the London catchment of the 'northern river'. Cherty ?Portlandian limestones higher in the sequence were probably also exposed. Outcrops of older Upper Jurassic formations were negligible and there is no indication of Middle or Lower Jurassic. Owing to solution, attrition and winnowing (see also Arkell, below, p. 165) of the pebbles, the relative sizes of the outcrops at any one time cannot be estimated.

The Upper Kimeridge–basal Portlandian pebbles gradually peter out south-eastwards across the Weald. The distant 'north-eastern river' was virtually devoid of them, though apparently carrying glauconitic sand of Portland origin (Allen, 1954). This suggests unconformable blanketing of the Kimeridge outcrops eastwards by overstepping Wealden, as already inferred on general grounds (*op. cit.*, text-figs. 1, 2).

Though the relative areas of the Upper Jurassic outcrops cannot be determined, evidence strongly suggests important changes during the Ashdown–Grinstead interval. By top Tunbridge Wells times the lydite beds' outcrops seem to have expanded considerably and those of the higher Portlandian to have decreased. This is consistent with the creation and southerly retreat of a Portland scarp and the destruction of flatter outliers north of it. General considerations indicate concomitant extension of the Upper Palaeozoics, a subject to be treated more fully later. These changes, of course, represent the beginning of a denudational sequence finally resulting in the transport southwards of much Oxford Clay as well as Palaeozoic detritus by Lower Greensand times (Arkell, 1939; Kirkaldy, 1947).

Intense leaching affected certain soils in the Uplands, probably over Old Red Sandstone outcrops supporting forests of gymnosperms.

ACKNOWLEDGMENTS

I wish to express my gratitude to many friends, particularly those cited above, for pondering so long and reporting so succinctly on the miserable Jurassic scraps now described. Thanks for assistance are also due to the Geological Survey of Great Britain and numerous landowners, and to the Research Board of Reading University who helped to defray the cost of purchasing the largest 'samples' and transporting them by lorry and car to Reading.

REFERENCES

ALLEN, P. 1949a. Wealden Petrology: The Top Ashdown Pebble Bed and the Top Ashdown Sandstone. *Quart. J. geol. Soc. Lond.*, **104**, 257.

———. 1949b. Notes on Wealden Bone-Beds. *Proc. Geol. Ass., Lond.*, **60**, 275.

———. 1954. Geology and Geography of the London–North Sea Uplands in Wealden Times. *Geol. Mag.*, **91**, 498.

———. 1959. The Wealden environment: Anglo-Paris basin. *Phil. Trans. Roy. Soc.*, **242**, 283.

———. 1960. Geology of the Central Weald: Study of the Hastings Beds. *Geologists' Association Centenary Guide. No.* 16.

ARKELL, W. J. 1939. Derived Ammonites from the Lower Greensand of Surrey and their Bearing on the Tectonic History of the Hog's Back. *Proc. Geol. Ass., Lond.*, **50,** 22.

———. 1947. The Geology of the Country around Weymouth, Swanage, Corfe and Lulworth. *Mem. geol. Surv. U.K.*

KIRKALDY, J. F. 1947. The Provenance of the Pebbles in the Lower Cretaceous Rocks. *Proc. Geol. Ass., Lond.*, **58,** 223.

MILNER, H. B. 1923. The Geology of the Country around East Grinstead, Sussex. *Proc. Geol. Ass., Lond.*, **34,** 283.

RELF, F. J. 1916. An Investigation of some Wealden Sands. *Geol. Mag.*, **3,** 295.

TOPLEY, W. 1875. The Geology of the Weald. *Mem. geol. Surv. U.K.*

APPENDIX

Report on Derived Jurassic Ammonites from the Top Lower Tunbridge Wells Pebble Bed

by the late W. J. ARKELL

1. DESCRIPTION, IDENTIFICATION AND AGE OF THE AMMONITES

224 specimens have been examined (Reading Geology Dept. Reg. Nos. S3–S226), obtained by Professor Allen from six tons of the pebble bed, at Hook Quarry, West Hoathly, Sussex. Most consist of or show parts of small fragments of internal casts of ammonites preserved in hard black phosphate, extremely rolled, mostly with a polished surface. The average size of the fragments is perhaps 10 mm. Few exceed 25 mm. in diameter. The largest [S72] is nearly half a whorl, 49 mm. long, but also very worn and polished. Most consist of internal casts of one or two camerae or parts of a camera.

The overwhelming majority represent an undoubtedly Upper Jurassic Perisphinctid fauna. Only two specimens [S225, S226] of those that can definitely be recognised as parts of an ammonite can be affirmed, from the whorl-sections, not to be Perisphinctids.

Although there is not a single specimen which, if standing alone, could be safely named, the assemblage considered as a whole is unequivocal and can be stated with certainty to represent the winnowings of a fauna of *Pavloviae* from the *rotunda* Zone of the Upper Kimeridge Clay.

Comparison has been made with 114 much better preserved small derived *Pavloviae*, belonging to at least six recognisable species, from the Lower Greensand of Wicken, Upware, Potton and Brickhill, in the Sedgwick Museum (Keeping, 1883). The combination of rolled and unrolled and partly rolled specimens provides the requisite standard for comparison with the wholly rolled Wealden fragments. Every Perisphinctid fragment in the Wealden collection is consistent, so far as it goes, with the characters exhibited by the Lower Greensand collection. A few of the Wealden fragments show sufficient characters, such as ribbing, constrictions, whorl section, or sutures, or combinations of two or more of these characters, to match one of the Cambridge species so closely that a specific name can be hazarded with reasonable justification (with, of course, the qualification 'cf.'). This applies especially to about a dozen fragments which seem to represent the following:

Pavlovia cf. *rotunda* (Sowerby). [S178].
P. cf. *kimmeridiensis* (von Seebach). [S72, S93].
P. cf. *gibbosa* (Buckman). [S3].
P. cf. *lyditica* (Buckman). [S83].
P. cf. *concinna* (Neaverson). [S171].
P. cf. *gracilis* (Neaverson). (But this last could also belong to some earlier Perisphinctid such as *Pictonia*). [S185].

In my opinion the whole Wealden collection, with the two exceptions mentioned, probably represents remains of ammonites of this group of species. One specimen has a marked ventral groove, but this is almost certainly spurious, resulting from loss of the siphuncle; it is a Perisphinctid, but not necessarily a *Pavlovia* (the specimen shows no ornament).

Of the two fragments that are not Perisphinctids, one [S225] is a single camera 9 mm. wide by 5.5 mm. high, with depressed elliptical whorl shape and no impressed area, which I cannot identify with any Jurassic genus or family. The other [S226] is also a single camera, 11 mm. wide and originally perhaps 19 mm. high, with tabulate venter and nearly flat, slightly convergent whorl sides. It retains no ornament but shows external and first lateral lobes of a suture. There are no ammonites with this whorl section in the British Jurassic above the *pseudomutabilis* Zone of the Lower Kimeridgian. It could be a fine-ribbed *Aulacostephanus* from the Lower Kimeridgian (fine-ribbed because if there had been coarse ribs as in the *A. eudoxus* group some trace of them might be expected to have survived), or a *Kosmoceras* (*Lobokosmokeras*) from the Oxford Clay. The suture precludes *Distichoceras*, and none of the numerous derived *Amoeboceras* from the Lower Greensand has the keel completely removed so as to leave a flat venter. On balance *Lobokosmokeras* is the most likely identification for this fragment.

2. COMPARISON WITH SOME OTHER DERIVED ASSEMBLAGES

For the closest analogue of the Wealden assemblage it is necessary to go to the lydite beds in the uppermost Kimeridgian and basal Portlandian of the outcrops from Swindon to Aylesbury (Neaverson, 1925; Arkell, 1933). The only collection that it has been possible to compare with the Wealden derivatives is a small one from the Upper Lydite Bed of Okus Quarry, Swindon (Geol. Survey. Mus. AT 2534–9), comprising twenty-five fragments. Without the indispensable preliminary systematic study, it is impossible to achieve reliable identifications, but by comparison with the Lower Greensand material from the Cambridge district it is possible to venture on the following preliminary list:

Pavlovia cf. *rotunda* (Sowerby) (6).
P. cf. *kimmeridiensis* (von Seebach) (3).
P. cf. *lyditica* (Buckman) (1).
P. cf. *concinna* (Neaverson) (1).
P. cf. *gracilis* (Neaverson) (1).
P. cf. small fragments indet. (12).

The Swindon specimens are much less rolled and less fragmentary than the Wealden, but this may be partly due to selective collecting, and in any case could be explained by the effects of a second derivation and further transport suffered by the Wealden material. Swindon, moreover, is the most remote of all the outcrops from the Weald. Closer agreement with the more easterly outcrops might be expected. [This has since been confirmed by collecting at Garsington, Wheatley (Littleworth) and Shotover in Oxfordshire.]

When allowance is made for these points, the conclusion follows that the Wealden assemblage was mostly likely derived from destruction of a phosphatic remainié bed at or near the top of the Kimeridge Clay, like those which crop out between Swindon and Aylesbury and in the Vale of Pewsey. The Dorset occurrence (Arkell, 1947) proves that such beds are not confined to the inland outcrops as previously supposed.

Three similar phosphatic nodule beds occur also in the upper part and at the top of the Kimeridgian in the Boulonnais (Pruvost, 1925; Dutertre, 1927), but the English Wealden pebbles are not derived from them, for all three contain many earlier ammonites such as *Pectinatites* (with the subgenera *Wheatleyites* and *Keratinites*) and *Subplanites*, in addition to the *Pavloviae* which are recorded from the top bed only. The pure culture of *Pavloviae* can be matched only from the English outcrops—so far as they are known.

3. CONCLUSIONS

The derived ammonites from the Wealden most nearly resemble, in preservation, degree of fragmentation and rolling, and also in palaeontological content, those in phosphatic nodule and lydite beds which occur in the top part of the Upper Kimeridge Clay and basal Portland Beds at outcrops in the west and north-west (Dorset, Wilts, Oxon, Bucks). Similar material occurs derived in the Lower Greensand of the Isle of Wight (Arkell, *in* Kirkaldy, 1947) remote from any known occurrence, and also in the Wealden of the Isle of Wight (Casey, *in* Allen, 1955), *in situ*.

The single Wealden fragment of ?*Kosmoceras* is anomalous, but the absence of such earlier Jurassic ammonites from the Kimeridgian and basal Portlandian lydite beds cannot be affirmed, because systematic collecting has not been done. Since these lydite beds contain Palaeozoic debris there would be no difficulty in accounting for the presence of an occasional earlier Jurassic fossil derived from some intermediate position between the Kimeridgian and Palaeozoic outcrops in late Jurassic times. The Cambridge [Lower Greensand] collections demonstrate that a range of fossiliferous strata, from Upper Oxford to high Upper Kimeridge Clay, can be eroded and yet the siftings may show only three or even two horizons if ammonites of the other horizons were not suitably preserved. The Middle and Lower Kimeridge and Upper and Lower Ampthill Clays are unrepresented at any of the Greensand localities near Cambridge, although the formations are all there, presumably because the ammonites were crushed during fossilisation. An equally wide range of formations could, therefore, have been drawn upon by the Wealden River with the production of an equally unrepresentative selection of winnowings.

REFERENCES

ALLEN, P. 1955. Age of the Wealden in north-western Europe. *Geol. Mag.*, **92,** 265.

ARKELL, W. J. 1933. *The Jurassic System in Great Britain.* Oxford.

———. 1947. Geology of the country around Weymouth, Swanage, Corfe and Lulworth. *Mem. geol. Surv. U.K.*, **82.**

KEEPING, W. 1883. *The Fossils, etc., of the Neocomian deposits of Upware and Brickhill.* Sedgwick Prize Essay, 1879.

KIRKALDY, J. F. 1947. Studies of pebbles from the Lower Cretaceous Rocks. *Proc. Geol. Ass., Lond.*, **58,** 232.

NEAVERSON, E. 1925. The Petrography of the Upper Kimmeridge Clay and Portland Sand in Dorset, Wiltshire, Oxfordshire and Buckinghamshire. *Proc. Geol. Ass., Lond.*, **36,** 240.

PRUVOST, P. 1925. Les subdivisions du Portlandien Boulonnais d'après les ammonites. *Ann. Soc. geol. Nord.*, **49,** 194.

DUTERTRE, A. P. 1927. Contribution à L'étude du Portlandien du Boulonnais. *Ann. Soc. geol. Nord.*, **51,** 240.

Pleistocene Sea-levels in North Devon

by MURIEL A. ARBER

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ABSTRACT: The ancient sea-cliffs of the North Devon coast are terraced by erosion surfaces which have already been described and attributed to the Pliocene by Professor Balchin. Two lower surfaces are now described: the Hele Surface (approximately 150 feet to about 100 feet O.D.) and the Croyde Surface (about fifty feet O.D.). Both these surfaces cut, and therefore post-date, the periglacial deposit of head. Such high sea-levels as those responsible for the Hele and Croyde Surfaces belong more probably to an Interglacial than to the Post-glacial period, and it is therefore suggested that the head was formed during the Penultimate Glaciation. The age of the buried channels of the Torridge and Taw is considered, and it is concluded that they may be older than the Penultimate Glaciation. The glacial erratics of Barnstaple Bay, and the neighbouring glacial Fremington Clay, underlie the head, and thus they too may belong to an older Glaciation than the Penultimate.

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1. INTRODUCTION

THE CLIFFS of the North Devon coast are interrupted only at Morte Bay, Croyde Bay, and the lowland occupied by the estuary of the Torridge and Taw (Fig. 1). This lowland is bounded by hills which are recognised as being a line of ancient sea-cliffs (Sedgwick & Murchison, 1836–7), and which bear signs of their earlier history in the form of erosion surfaces, the upper members of which have been investigated by Balchin (1952). My own independent observations on the erosion surfaces, both here and farther west in North Devon, were begun in 1943 and were almost completed before Professor Balchin first announced in 1950 the results of his work on Exmoor and on the Torridge and Taw estuary. Like him, I had found that the terracing cuts across the highly folded beds so that the surfaces are independent of lithology and structure. His summit levels and his Exmoor, Lynton and Molland Surfaces are all higher than the highest ground in the western part of North Devon, but there is a possible relic of his Anstey Surface (ranging from approximately 825 feet down to about 700 feet) near Welcombe Cross (261183), and remains of what are probably his Buckland Surface (from about 675 feet to below 500 feet), his Georgeham Surface (425 feet down to 300 feet), and his Instow Surface (280 feet down to below 200 feet).

The only direct evidence of the age of these surfaces is given by the flint gravels of Orleigh Court (429223) at Buckland Brewer, which rest on the Georgeham Surface and were considered by I. Rogers & Simpson (1937) to be probably of Pliocene date. The Instow Surface also was attributed by Balchin to the Pliocene. Balchin (1952) and Wooldridge (1954) consider that all these platforms probably owe their existence to eustatic changes of sea-level, but King (1954) suggests that they were in their origin Triassic pediment surfaces which have been uplifted at various times and tilted or warped in the Miocene or even the early Pliocene period.

I have also observed two lower levels: one, for which I here suggest the name of the Hele Surface, ranging from rather more than 150 feet down to

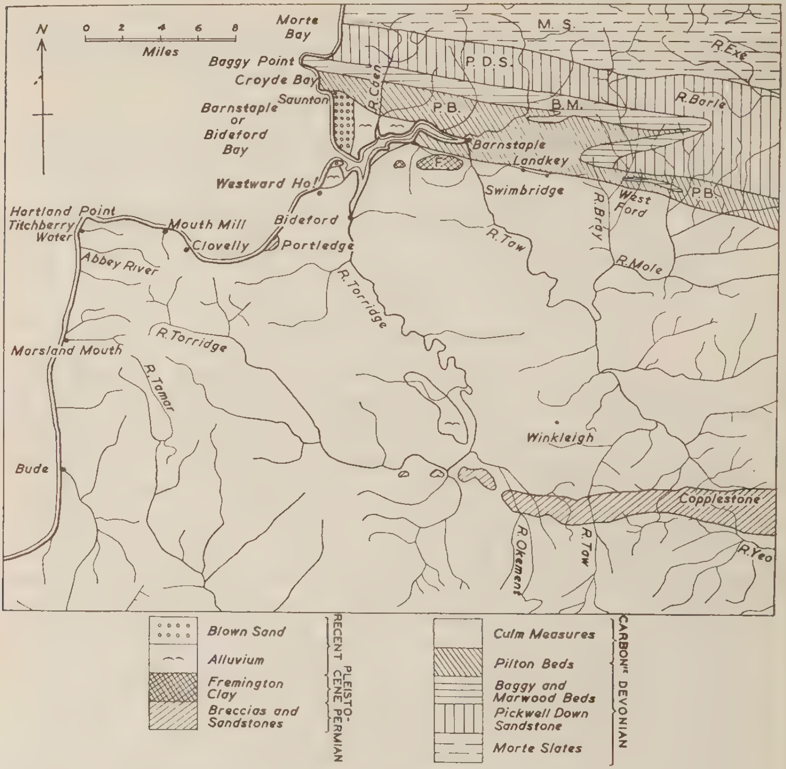
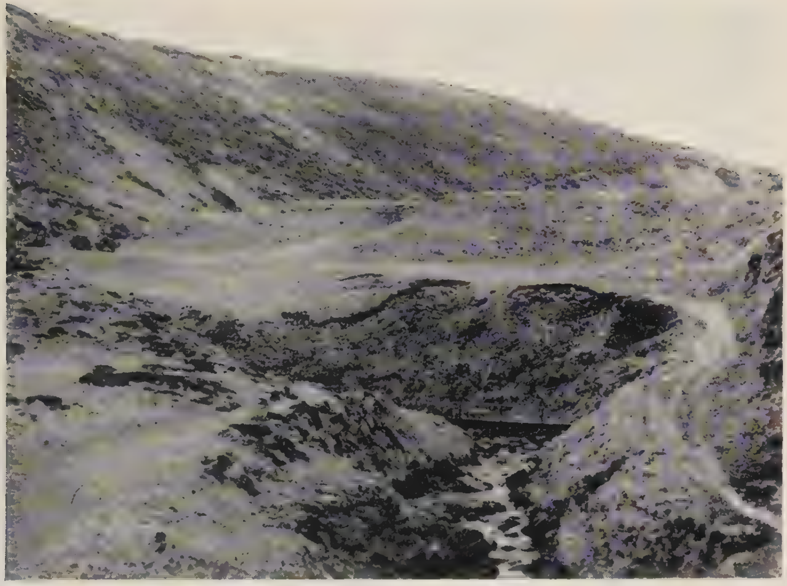
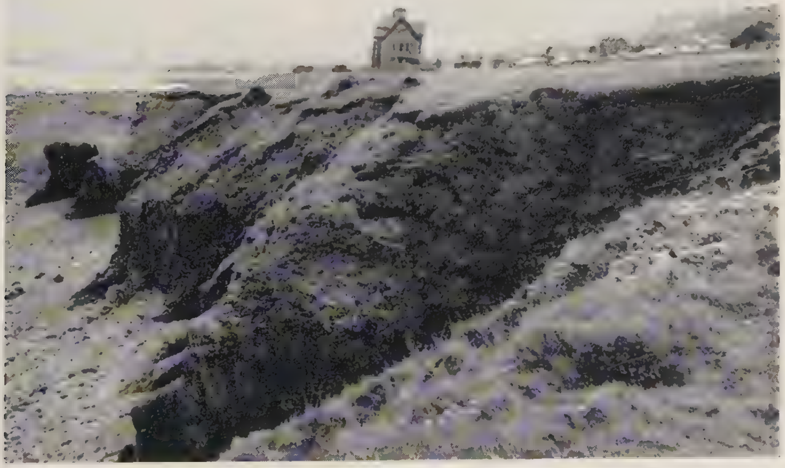


Fig. 1. Geological sketch-map of that part of North Devon which is drained by the Torridge and Taw



A. Terraces in head at Marsland Mouth



Photos by M.A.A.

B. Raised beach and head at Westward Ho!

about 100 feet (Plate 7A), and the other, which I have here called the Croyde Surface, at about fifty feet. I first noticed the apparent existence of these surfaces in the field and then tried to estimate their heights with the help of Ordnance Survey maps and a rough check by aneroid, but it has not been possible for me to attempt the surveying or statistical analysis which are needed to confirm or disprove the actual existence of these surfaces, and, if they are found to exist, to establish their exact height. I hope that this study may be carried out by other workers.

The coast of North Devon is included in the Ordnance Survey one-inch sheets 163 and 174. The whole area concerned falls within the National Grid square 21 (SS), which number should therefore be prefixed to complete all the grid references in this paper. North Devon has not been mapped on the one-inch scale by the Geological Survey since 1839, but the geology of the area (Fig. 1) has been summarised, with a bibliography, by Dewey (1948).

2. LOW LEVEL EROSION SURFACES

(a) Hele Surface

This surface, ranging from rather more than 150 feet down to about 100 feet, is a conspicuous feature both of the Torridge and Taw estuary and of the coast south of Hartland (Plate 7A). In Morte Bay also, the waterfall (455445) above Combegate Beach, between Mortehoe and Woolacombe, descends to the sea from a valley-floor 100 feet above. The surface is seen on both banks of the Taw near Barnstaple, including the area around Hele (546321) and Bickington (534325) which forms the seaward side of the Fremington valley, and it occurs on both banks of the Torridge near Bideford, where Hallsannery (457245) is built on it. South of Hartland Point it is found at Titchberry Water (Fig. 1; 229267) and Smoothlands (226265), for the height of Smoothlands was wrongly stated to be only fifty feet by E. A. N. Arber (1911, 236) and unfortunately his mistake misled Green (1943, 134) although the height is correctly shown as 100 feet in Arber's map (Arber, 1911, 235). At Marsland Mouth (Fig. 1; Plate 7A; 213174) on the Cornish border, a river terrace at about 100 feet has been cut in the head filling the valley.

The head is apparently a solifluction deposit, formed under periglacial conditions. The Hele Surface cuts across the head, and must therefore have been developed after a glacial period.

An alteration in the drainage of the valleys at Barnstaple can be dated as having occurred in connection with this change of sea-level. The valley joining the Taw from the south-east at the point where Barnstaple now stands (Fig. 1) is shown in Balchin's maps of the Georgeham and Instow coastlines. By the Hele stage, the river draining this valley would have been flowing below the level of the 185 foot col (596316) at Landkey, and must have been diverted into its present course westwards, to join the Taw at Bishop's Tawton (Fig. 1), thus leaving a dry gap at Landkey and a wide valley now occupied by a small stream between Landkey and Barnstaple.

There are other records of levels at 100 feet in Wales, south-west England, and Brittany. Brown (1952) has described the 100 foot Crosswood Stage in the Ystwyth valley; Trueman (1939) has recorded levels at this height in the river valleys near Bristol, and Guilcher (1949) considers that the 100 foot level at Plymouth recalls conditions in Brittany.

(b) Croyde Surface

This surface, at about fifty feet, is found round the Taw and Torridge near Barnstaple and Bideford. Pilton (557340) stands on a marked spur at this level, which is here given the name of the Croyde Surface on account of its wide development in the Croyde valley (Fig. 1). The frequently sharp break between its upper limit at about fifty feet and the lower limit of the Hele Surface above at about 100 feet, is marked by a river-cliff, which is an almost sheer slope cut in solid rock, in Anchor Wood (543328) on the left bank of the Taw downstream from Barnstaple, and by a corresponding river-cliff on the left bank of the Torridge between Bideford and Appledore. A level at fifty feet in the valleys near Bristol has been recorded by Trueman (1939).

In Croyde Bay and at Westward Ho! (Plate 7B), the head overlying the raised beach is levelled off at this height as is the head in the valleys of Mouth Mill (Fig. 1; 298266) west of Clovelly, and of the Abbey River (Fig. 1; 226257) at Hartland, while at Marsland Mouth (Plate 7A) the fifty foot surface forms a pair of terraces in the head below the 100 foot terrace. This shows that the Croyde Surface, as well as the Hele Surface, is younger than the head, and may have been cut during the period of high sea-level which would also have been responsible for the line of old raised sea-cliffs behind Morte Bay.

3. THE DATING OF THE HELE AND CROYDE SURFACES

In attempting to date the fluctuations of sea-level recorded by the Hele and Croyde Surfaces, their possible relation to the buried channels and to the raised beach deposits must be considered. In the estuary of the Torridge and Taw, deep channels, now buried beneath sand and clay, have been surveyed seismically by McFarlane (1955). He estimated that the old channels were eighty-five feet below O.D. at their confluence, and about 100 feet below O.D. at their mouth, and he suggested that, when they were cut, sea-level must have been about 150 feet lower than at the present day, thus displacing the shore-line about eight miles out into Barnstaple Bay. McFarlane did not attempt to date the channels, but they presumably post-date the Georgeham and Instow Surfaces when sea-level stood some 425 and 280 feet respectively above its present level.

The mouths of the smaller valleys are often filled with head in which the streams have incised small gorges (Plate 7A), but there is no sign of deep channels in the head such as one might expect if sea-level had dropped very far since the head was deposited. If, however, one could strip these valleys of their infilling of head, they would be much deeper than they are now, though with a solid rock-floor still above present sea-level, and this suggests that they were carved by streams graded to a lower sea-level than that of subsequent periods. Thus the evidence points to the time of low sea-level having preceded the time at which the head was deposited, and consequently being considerably earlier than the high sea-levels which were responsible for the Hele and Croyde Surfaces.

The raised beach platform of Barnstaple Bay (Plate 7B) is estimated to be about thirty feet O.D. where it is exposed near the foot of the ancient sea-cliffs at Westward Ho! (E. H. Rogers, 1946) and Baggy Point (Green, 1943). There is no clear evidence as to whether the high sea-level responsible for this platform preceded or, as seems more probable, followed the fall of sea-level indicated by the buried channels of the estuary, but since it must have preceded the deposition of the raised beach deposits and head, then it must also have preceded the high sea-levels in which the Hele and Croyde Surfaces were cut in the head.

The concept of the Croyde Surface may solve the problem discussed by E. H. Rogers (1946) of the varying height of the Westward Ho! platform, which is at about thirty feet O.D. near Rock Nose (420291) but drops to seven feet at the Baths 600 yards to the east. As J. F. N. Green suggested to E. H. Rogers (Rogers, 1946) this is due to the fact that the present shore-line runs obliquely to the old shore-line of the raised beach platform, so that the sections in which the platform is lower are those nearer to the old low water mark, while those in which it is higher are nearer the notch at the foot of the old cliff behind the raised beach. This solution was rejected by Rogers on the ground that the platform continued to dip even when the present shore-line ran parallel to the fifty foot contour line which Green took to represent the old cliff, but if one accepts the idea that the fifty foot contour marks the rise of sea-level which cut the Croyde Surface, then the old cliff-line is not necessarily indicated by this contour but must lie buried behind the head.

The Westward Ho! raised beach platform (Plate 7B) is overlain by an accumulation of rounded pebbles, in turn overlain by head. At Saunton and Croyde, however, the deposits immediately above the raised beach platform include erratics, amongst them the well-known pink gneissose granite boulder at Saunton (Hughes, 1887; Dewey, 1910, 1913; Taylor, 1956, 1958) which was probably brought from the west coast of Scotland.

Dewey regarded the erratics as having been transported by floating ice but Zeuner (1945) inclined to the view that they were derived from the moraine of a glacier which deposited the neighbouring Fremington Clay in the Penultimate or some earlier Glaciation. Above the glacial boulders on the Saunton raised beach come current-bedded sands with shells of a temperate fauna, and above these again lies the head. All these have been discussed by Arkell (1943) and he subsequently re-dated them (Arkell, 1945). He considered that materials on a ten foot (*Patella* beach) of Riss age must have existed at Saunton and have included the erratic boulders which have remained in their original positions; the other deposits, however, were reworked and redeposited during a period of warm climate, as indicated by the fauna; this, he suggested, was the Riss–Würm Interglacial. Later in the same period, they were buried under a deposit of blown sand. The head, which in turn overlies the sand, was attributed by Arkell to the Würm Glaciation.

If Arkell's second dating of the head be accepted, the rise of sea-level to about 100 feet which cut the Hele Surface, followed by the fall which cut the Croyde Surface at fifty feet above present sea-level (Plate 7B), must have taken place in the Post-glacial period. Such a height of sea-level in Post-glacial times seems, however, to be improbable; the post-glacial fluctuations revealed by deposits on the foreshore at Westward Ho!, some of which are dateable as Mesolithic (E. H. Rogers, 1946) and Neolithic (I. Rogers, 1908) respectively, indicate relatively minor movements. Thus it would be much more likely that the head after all belongs not to the Würm but to the Riss Glacial period as Arkell (1943) at first suggested. Attempted correlation of local sequences with the Alpine sequence of the Pleistocene is in itself at present unsatisfactory, and it might be better to say that the head of North Devon appears to belong to a period not later than the Penultimate Glaciation.

The presence, below the head and above the glacial erratics, of shells of a temperate fauna indicating an Interglacial, suggests that the glacial erratics themselves and the beach on which they lie may be of a still earlier date than the Penultimate Glaciation, a possibility which Zeuner foresaw. The suggestion has been made in this paper that the buried channels of the rivers are older than the raised beach deposits; thus the buried channels also may belong to a period earlier than that of the Penultimate Glaciation. However, all such attempts at dating and correlation must be considered simply as working hypotheses until more evidence is forthcoming.

4. CONCLUSIONS

Evidence has been brought forward to show that in North Devon the head, which is accepted as being a periglacial deposit, is levelled by a surface ranging from rather more than 150 feet down to about 100 feet, and here named the Hele Surface, and by a lower surface, here named the Croyde Surface, at about fifty feet above present sea-level. Such high sea-levels are not likely to be of later date than the last Interglacial, and the head may therefore belong to the Penultimate Glaciation. The head itself is younger than the glacial erratics of North Devon, which may therefore belong to a still earlier Glaciation. In the absence of direct evidence as to the date of the buried channels of the Torridge and Taw, indirect evidence suggests that the period of low sea-level to which they belong may also be older than that of the Penultimate Glaciation.

It must once again be emphasised that, until more work has been done on the area, some of the estimated heights in relation to present sea-level are approximations only, and that the suggested dating of many of the episodes is regarded as purely tentative.

EXPLANATION OF PLATE 7

A. Marsland Mouth, looking upstream eastwards from 213174; north bank in Devon, south bank in Cornwall. Valley-side of Culm Measures in background. Upper terrace (Hele Surface at approximately 100 feet) and lower terrace (Croyde Surface at fifty feet) cut in head which fills valley-floor.

B. Raised beach platform of almost vertical Culm Measures between Rock Nose and Westward Ho!; overlain by raised beach deposit of pebbles, with head above levelled by Croyde Surface (fifty foot contour is at edge of cliff). Looking towards Westward Ho! from 422291.

REFERENCES

Arber, E. A. N. 1911. *The Coast Scenery of North Devon.* London.

Arkell, W. J. 1943. The Pleistocene Rocks at Trebetherick Point, North Cornwall: their Interpretation and Correlation. *Proc. Geol. Ass., Lond.*, **54**, 141–70.

———. 1945. Three Oxfordshire Palaeoliths and their Significance for Pleistocene Correlation. *Proc. prehist. Soc.* (N.S.), **11**, 20–31.

Balchin, W. G. V. 1952. The Erosion Surfaces of Exmoor and Adjacent Areas. *Geogr. J.*, **118**, 453–76.

Brown, E. H. 1952. The River Ystwyth, Cardiganshire: a Geomorphological Analysis. *Proc. Geol. Ass., Lond.*, **63**, 244–69.

Dewey, H. 1910. Notes on some Igneous Rocks from North Devon. *Proc. Geol. Ass., Lond.*, **21**, 429–34.

———. 1913. The Raised Beach of North Devon: its relation to others and to Palaeolithic Man. *Geol. Mag.* (N.S., 5), **10**, 154–63.

———. 1948. South-West England. Second Edition. *Brit. reg. Geol.*

Green, J. F. N. 1943. The Age of the Raised Beaches of South Britain. *Proc. Geol. Ass., Lond.*, **54**, 129–40.

Guilcher, A. 1949. Aspects et problèmes morphologiques du massif de Devon–Cornwall comparés à ceux d'Armorique. *Rev. Géogr. alp.*, **37**, 689–717.

Hughes, T. McK. 1887. On the Ancient Beach and Boulders near Braunton and Croyde, in N. Devon. *Quart. J. geol. Soc. Lond.*, **43**, 657–70.

King, W. B. R. 1954. The Geological History of the English Channel. *Quart. J. geol. Soc. Lond.*, **110**, 77–101.

McFarlane, P. B. 1955. Survey of Two Drowned River Valleys in Devon. *Geol. Mag.*, **92**, 419–29.

ROGERS, E. H. 1946. The Raised Beach, Submerged Forest and Kitchen Midden of Westward Ho! and the Submerged Stone Row of Yelland. *Proc. Devon. archaeol. Explor. Soc.*, **3** (3), 109–35.

ROGERS, I. 1908. On the Submerged Forest at Westward Ho! Bideford Bay. *Rep. Devon. Ass. Adv. Sci.*, **40**, 249–59.

——— & B. SIMPSON. 1937. The Flint Gravel Deposit of Orleigh Court, Buckland Brewer, North Devon. *Geol. Mag.*, **74**, 309–16.

SEDGWICK, A. & R. I. MURCHISON. 1836–1837. Description of a Raised Beach in Barnstaple Bay, on the North-West Coast of Devonshire. *Proc. geol. Soc. Lond.*, **2** (48), 441–3.

TAYLOR, C. W. 1956. Erratics of the Saunton and Fremington Areas. *Rep. Devon. Ass. Adv. Sci.*, **88**, 52–64.

———. 1958. Some Supplementary Notes on Saunton Erratics. *Rep. Devon. Ass. Adv. Sci.*, **90**, 187–91.

TRUEMAN, A. E. 1939. Erosion Levels in the Bristol District, and their relation to the Development of the Scenery. *Proc. Bristol Nat. Soc.* (4), **8** (4) (for 1938), 402–28.

WOOLDRIDGE, S. W. 1954. The Physique of the South West. *Geography*, **39**, 231–42.

ZEUNER, F. E. 1945. The Pleistocene Period. Its Climate, Chronology and Faunal Successions. *Ray Soc. Publ.*, 130.

———. 1959. Second Edition, London.

New Sections in the Corallian Beds around Oxford, and the Subzones of the *Plicatilis* Zone

by J. H. CALLOMON

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ABSTRACT: A number of new temporary exposures in the Corallian beds near Oxford are described. The many ammonites obtained are listed, together with further material from old quarries in neighbouring areas. On the basis of these faunas the *Plicatilis* Zone can be subdivided into three subzones.

These subzones can also be recognised in other areas further afield when the ammonites obtained from them in the past are re-examined, and suggest that a number of stratigraphical correlations, based previously on lithological comparisons, need to be revised.

1. INTRODUCTION

FOLLOWING THEIR OUTCROP from the Dorset coast inland across southern England, the Corallian beds show a rapidity of facies-changes probably unequalled in the British Jurassic before they change finally almost wholly into clays a few miles east of Oxford. Along this outcrop the last thirty miles form a convenient unit, the Faringdon–Oxford ridge, bounded in the west by a temporary thinning of the beds about three miles west of Highworth, and in the east by the change to clays near Beckley and Stanton St. John, five miles east of Oxford. It is by far the best known part of the Corallian (and the only one to be considered here), due largely to work extending over twenty years by W. J. Arkell.

The Faringdon–Oxford ridge may be conveniently subdivided into five areas (see Fig. 1). In each, more or less standard successions have been established through study of sections exposed in widely scattered quarries, many of which have now fallen into disuse. The Corallian beds are rich in ammonites and Arkell's monograph (1935–48) makes the Corallian group of ammonites one of the best known. Much of the material on which this monograph was based came from the Faringdon–Oxford ridge, but as in so many cases, most of the material in the older collections was without sufficient evidence of origin to be of use for stratigraphical purposes. Against this, Arkell himself collected some 200 specimens in the region, mostly from accurately known horizons; but these proved to be just insufficient for making finer correlations between beds within the formations, as no sufficiently systematic changes could be detected in successive faunas. With the failure of ammonites to provide accurate marker horizons over longer distances, the correlation of beds up to now has been based mainly on comparisons of lithology in adjacent areas of the ridge, and on the results of surface mapping. Three lithological series, in descending order, are recognised: Osmington Oolites, Berkshire Oolites, and Lower Calcareous Grit. The classification of beds into these series is summarised by Arkell (1947, 76, 85). All belong to the one ammonite zone of *Perisphinctes plicatilis*, although a provisional attempt has been made (Arkell, 1947, 98) to identify the three series with three subzones.

Considering the five subdivisions of the Faringdon–Oxford ridge in more detail, by far the largest number of ammonites has been obtained from areas I–III at the eastern end. In addition, the best-known sections are in areas I and III: provided, in the former, by the quarries of the Beckley area (Arkell, 1936, 171; Callomon, 1953); and in the latter, by the quarries at Cothill and Marcham (described by Arkell, 1936, 156). Unfortunately, most of the ammonites obtained in the past from the intermediate area II came from quarries around Headington, which show highly condensed sequences; or, including most of those in the old collections in the Oxford University Museum and much of the material collected by Buckman, from temporary or unrecorded exposures now extinct.

It is the purpose of this paper to describe a number of new sections which have been recorded in temporary exposures lying in area II, in the triangle between Sandford-on-Thames, Cowley and Garsington, and which have yielded many ammonites. Further ammonites from the now disused quarries at Cothill, in area III, are also listed. With this new information,

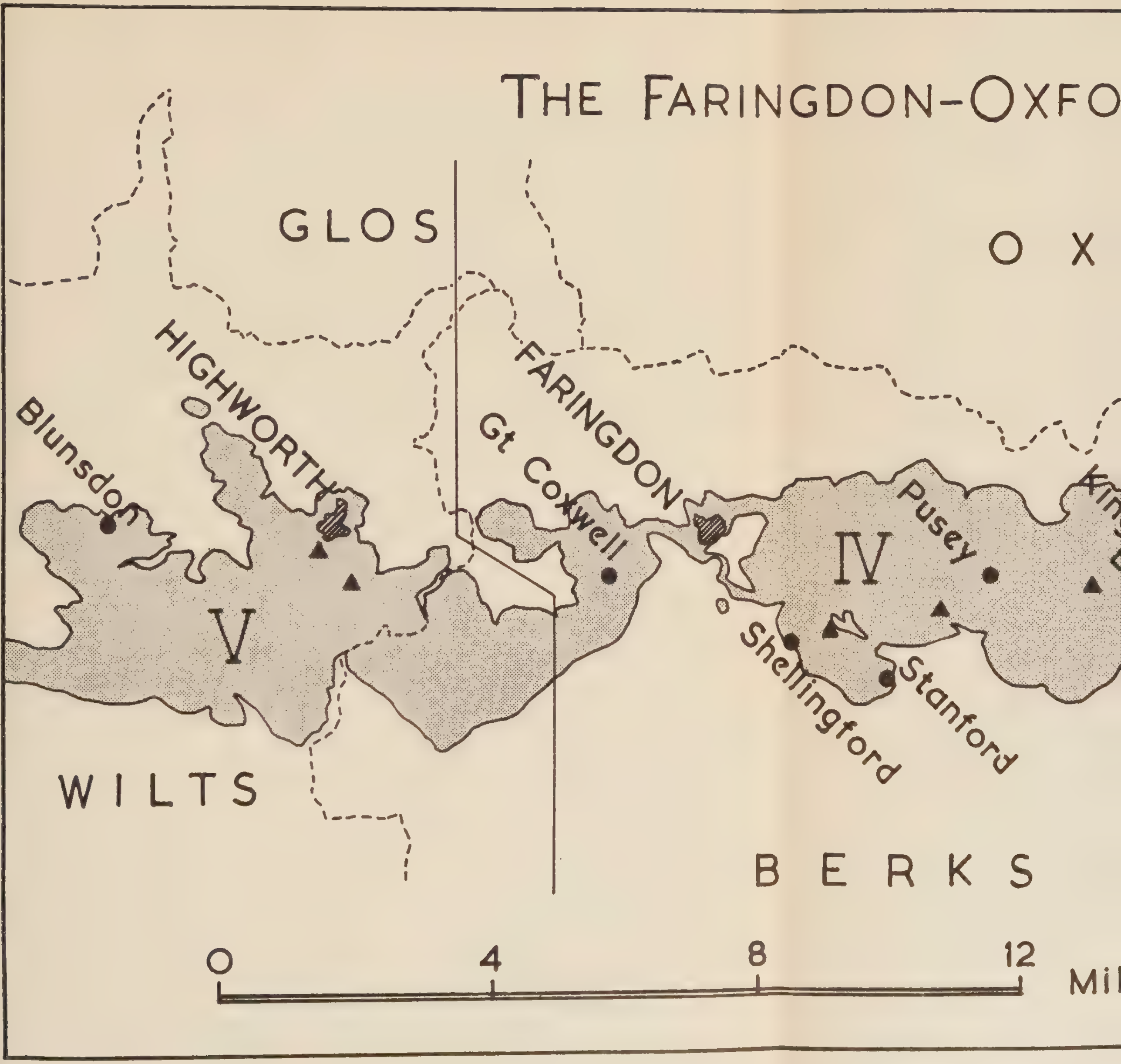
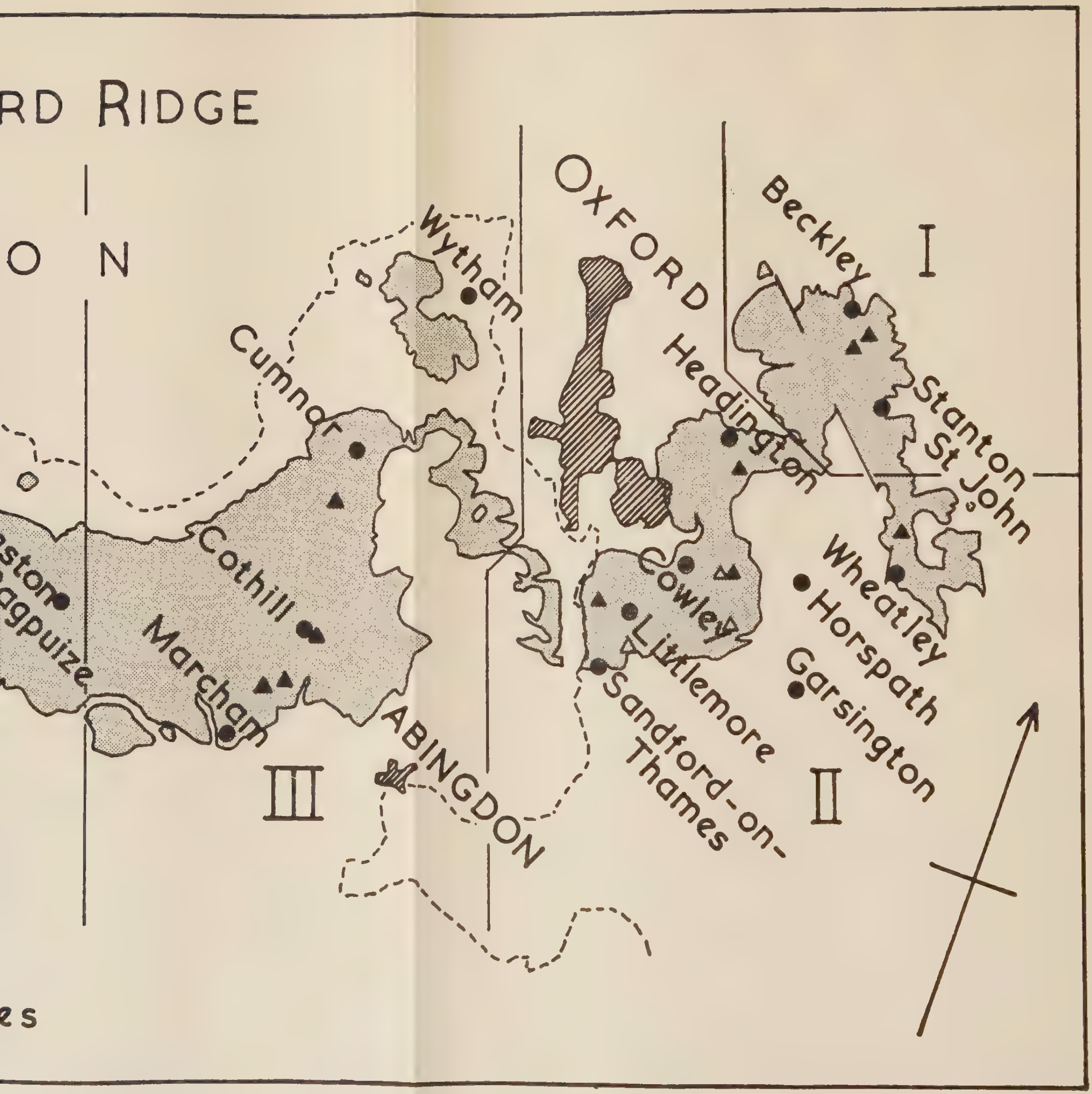


Fig. 1. Map of the Faringdon–Oxford Ridge. Outcrop of Oxfordian in rock



cies shaded. Solid triangles, quarries; open triangles, temporary exposures

[*To face p.* 178

the *Plicatilis* Zone can be subdivided into three ammonite subzones clearly recognisable in areas I–III, and an attempt can be made to correlate beds according to their ammonites rather than lithology. Extrapolation westwards suggests that these correlations can be extended to areas IV and V, and possibly farther afield, and that the subzones cut across the lithological boundaries of Osmington and Berkshire Oolites.

2. THE SECTIONS

The three subzones to be recognised are:

subzone of *Perisphinctes* (*Perisphinctes*) *parandieri* de Lor. (top)
Perisphinctes (*Dichotomosphinctes*) *antecedens* Salfeld.
Cardioceras (*Vertebriceras*) *vertebrale* Buck. (bottom)

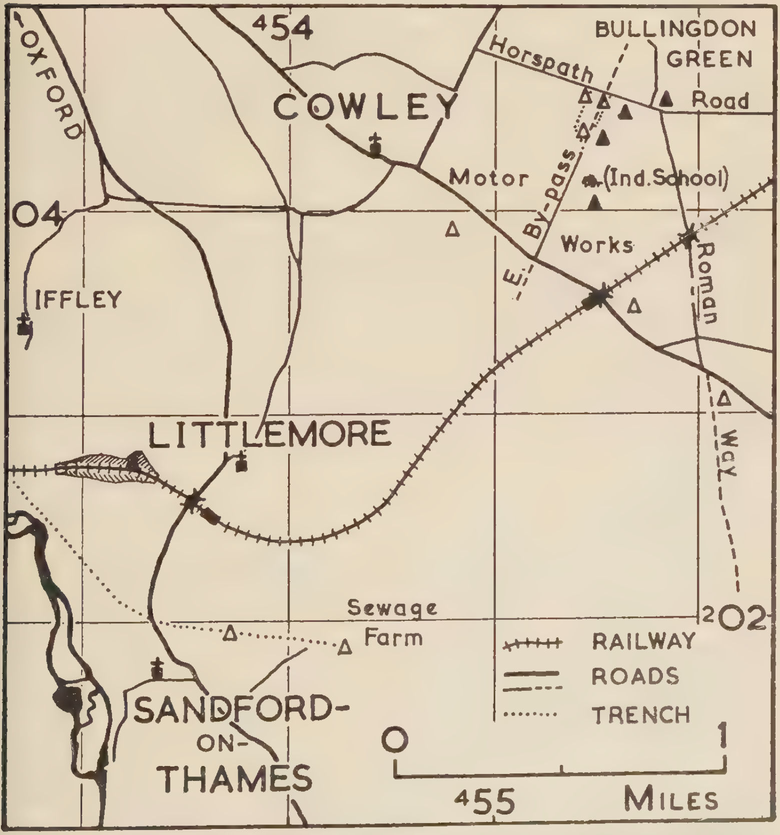


Fig. 2. Map of part of Area II. Solid triangles, quarries; open triangles, temporary exposures

and their palaeontological basis will be discussed below. Where possible, they will be indicated in the descriptions of sections which follow. Names and authors of species are as in Arkell's monograph.

Numbers behind the names of ammonites refer to the Oxford University Museum collections, except where otherwise indicated. The following abbreviations will be used: O.U.M., Oxford University Museum; G.S.M., Geological Survey Museum; M.C.A., Monograph of the English Corallian Ammonites by Arkell.

The localities of the sections described, together with certain older ones discussed below, are marked on a map (Fig. 2). Some of the more important sections are shown diagrammatically in Fig. 3. Shell-beds are numbered consecutively in each section.

Section (a)

Main pipe trench to new sewage processing plant, Sandford-on-Thames, extending from the main Dorchester road (533020) half mile eastwards.

parandieri Subzone — Osmington Oolites: Littlemore Clay Beds

	ft.	in.
22. Clay, brown	1	7
21. Clay, marly, yellowish, and mudstone rubble	2	4
20. Clay, light bluish-grey	0	9
19. Clay and marl, white, with mudstone	1	2
18. Clay, grey	0	4
17. Limestone rubble, argillaceous, white	1	5
16. Clay, brown	0	11
15. Clay and marl, white, with mudstone	2	1
14. Clay, blue	0	10
13. Marl, cream	1	6
12. Clay, grey	0	9
11. Limestone, cream, marly and rubbly	2	6
10. Sand, yellowish	1	5
9. Clay, brown	0	3

Perisphinctes (*Perisphinctes*) *de riazi* Siemiradzki (J3856) not in place, beds 11–21 by matrix

?antecedens Subzone

	ft.	in.
8. Sand, clayey, with some limestone	1	1
7. Limestone, impersistent, shelly	0	6
6. Clay, marly, brown and white	0	11

Berkshire Oolites

	ft.	in.
5. Sand, yellow	0	8
4. Limestone rubble	0	6
3. Sand, yellow	2	6

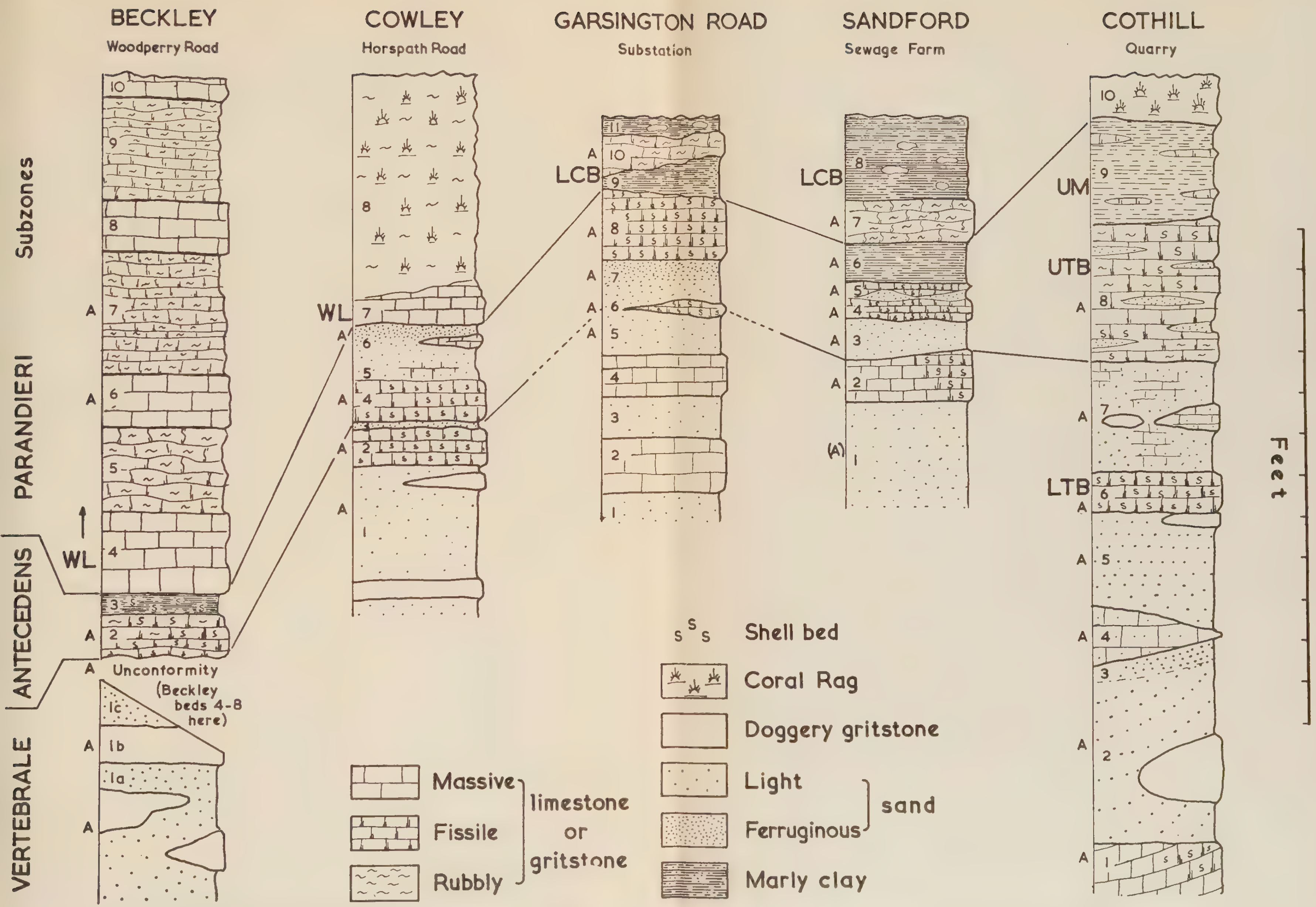


Fig. 3. Diagrammatic representation of some important sections. *WL* = Wheatley Limestone; *LCB* = Littlemore Clay Beds; *UM* = Urchin Marls; *UTB* = Upper Trigonia Bed; *LTB* = Lower Trigonia Bed. Beds yielding ammonites are marked *A*

vertebrale Subzone	ft.	in.
2. Shell Bed I: grey, purplish-brown flaggy shelly limestone or gritstone with thin layers of brown sand and clay, locally weakly oolitic. *Gervillella aviculoides* (Sow.), *Chlamys fibrosa* (Sow.), *Ostrea* sp.		
Perisphinctes (*Arisphinctes*) *ingens—cotovui* (J3857) *Cardioceras* (*Subvertebriceras*) sp.		
1c. Sand, yellow, even-bedded	2 to 3	0
b. Gritstone, grey, hard, impersistent	0 to 1	6
a. Sand, yellow, even-bedded	seen to 12	0
P. (*Arisphinctes*) *cotovui*, part of a large body-chamber		

This section is broadly similar to that in the Littlemore railway cutting, half mile to the NW. (Pringle, 1926, 52; Arkell, 1927, 141) (Fig. 2), although many changes have occurred in even such a short distance. The Shell Bed 2 above is the same as Pringle's bed 3; thereafter close correlations become more difficult, although beds 11 and 15 probably correspond to Pringle's beds 15 and 21 respectively. Pringle published Buckman's identifications of the poorly preserved ammonites which had been found, but these had already been queried by Arkell (1927) and are unsound. The ammonites (in the G.S.M.) have now been re-examined and renamed on the basis of Arkell's monograph; and, together with further finds, the list from Littlemore cutting is now as follows:

Littlemore Clay Beds:
Beds 27, 21: *P.* (*Dichotomosphinctes*) cf. *buckmani* (G.S.M. SH4775–8)
15: *P.* (*?Kranaosphinctes*) sp. (SH4722)

Berkshire Oolites:

7:	*P.* (*Perisphinctes*) sp., published as '*Aspidoceras* sp.'	(SH4721)
3:	*P.* (*Dichotomosphinctes*) *rotoides*	(SH4717)
	P. (*Arisphinctes*) cf. *cotovui*	(O.U.M. J4540)
	pickeringius	(J3851)
	helenae	(J11,524)
	(*Kranaosphinctes*) cf. *trifidus*	(J3849)
	cymatophorus	(J3848)
	decurrens	(J6137)
	C. (*Subvertebriceras*) *densiplicatum*	(J12,757
	C. (*Vertebriceras*) cf. *vertebrale*	(SH4719)
	C. (*Scoticardioceras*)	(SH4713)
	Goliathiceras cf. *chamoussetiforme*	(J1567)

Section (b)

Excavations for new sewage processing plant, Sandford-on-Thames (542019), half mile east of the church; Figs. 2 and 3.

The main section was provided by a large shallow hole dug with bulldozers for the foundations of aeration tanks. About three feet of limestones, marls and sands were exposed (beds 2–6), the material removed forming large tip-heaps. Lower beds were exposed in other excavations farther to the east, and the higher beds were seen in trenches cut for pipes.

Topsoil
Osmington Oolites
Littlemore Clay Beds

?parandieri Subzone — ft. in.

8. Marl, brown, with lumps of white limestone 2 0
7. Limestone, cream, argillaceous, rubbly; few fossils. *G. Aviculoides*, *Chlamys fibrosa*
   P. (*Dichotomosphinctes*) *buckmani* (J3884, 3896) ... about 1 0

antecedens Subzone

6. Clay, greenish, marly... ... ... 1 0
   P. (*Arisphinctes*) *cotovui* (J3870, 3872)
   kingstonensis (J3888)

Berkshire Oolites

5 and 4. Shell Beds III and II: limestone, grey with red stains, shelly, hard, impersistent in clayey sand, a mass of fossils; and grey shelly gritstone or sandy limestone. *Gryphea* sp., *Trigonia huddlestoni* Lycett and sp., *G. aviculoides* (Sow.) profuse, *Chlamys splendens* (Goldfuss), *C. fibrosa* (Sow.); *Nautilus* (*Paracenoceras*) *hexagonus* Sow. 0 10

P. (*Dichotomosphinctes*) *buckmani*	(J3868)
antecedens	(J3893)
(*Arisphinctes*) *ingens*	(J3880)
cotovui	(J3871–7)
pickeringius	(J3862, 3867)
kingstonensis	(J3881)
(*Kranaosphinctes*) cf. *promiscuus* Buk.	(J3894, 3901)
sp. nov. *H*	(J3879)
(*Liosphinctes*) *apolipon*	(J3860, -61, -95)
aff. *apolipon* sp. *F*	(J3858, -89)
cf. *linki* Arkell non Choffat sp. *E*	(J3859, -64, -66, -97)
aff. *laevipickeringius* sp. *D*	(J3882)
C. (*Subvertebriceras*) *zenaidae*	(J3906)
cf. *densiplicatum*	(J3907)

3. Sand, yellow, and marly clay *Chlamys fibrosa* 0 8
   P. (*Dichotomosphinctes*) cf. *antecedens* (J3900)
   rotoides (J3885, 3899)

vertebrale Subzone

2. Shell Bed I: sandy limestone or gritstone, grey, slabby, many fossils ... ... 1 to 1 3
   Trigonia huddlestoni Lycett, *T.* sp., *G. aviculoides* (Sow.), *Ch. fibrosa* (Sow.)
   P. (*Arisphinctes*) *cotovui* (J3887) *P.*
   (*Kranaosphinctes*) *decurrens* (J3886)
   Aspidoceras sp. (J3885)
1. Sand, yellow ... ... seen to 3 0

This succession resembles closely one described by Cobbold (1880, 317, fig. 6).

Section (c)

Cowley 33 kV electricity substation, Garsington Road: trenches for foundations, at junction of road to Stadhampton and Roman road, half mile SE. of Morris Cowley station (561031) (Figs. 2 and 3).

Osmington Oolites:
Littlemore Clay Beds and Wheatley Limestones

parandieri Subzone — ft. in.

11. Clay, loamy, dark brown with worn lumps of corals, *Isastraea* and *Thamnasteria* 0 6
10 and 9. Limestone, cream, marly nodular rubble; passing into clay, grey marly ... ... 0 4 to 1 0

P. (*Dichotomosphinctes*) *buckmani* (J10,267)
cf. *antecedens* (not coll.)
P. (*Perisphinctes*) cf. *parandieri* (J10,265)
cf. *chloroolithicus* (J10,263)
P. (*Arisphinctes*) cf. *parandiformis* (J10,274)
cotovui (J10,281, -84)

antecedens Subzone

8. Shell Bed: limestone or gritstone, dark grey, rubbly, stained brown and red in places, many lydite pebbles, a mass of fossils; lamellibranchs, especially *Gervillella*, and belemnites ... 1 6

P. (*Dichotomosphinctes*) *antecedens* (J10,264, -66, -70)
cf. *auriculatus* (J10,269)
P. (*Arisphinctes*) *cotovui* (J10,280)
cf. *cowleyensis* (not coll.)
P. (*Liosphinctes*) *apolipon* (several fragments, not coll.)
Aspidoceras cf. *crebricostis* (J10,268)

7. Sand, red-brown, marly, with quartz pebbles; many fossils, including 'derived' ammonite fragments preserved in dense cream oolite (marked 'ool.' in the list below). *Nucleolites scutatus* (Lam.) abundant, *Ostrea quadrangularis* Arkell, many *Exogyra* and Serpulae; *Pachyteuthis abbreviatus* (Phillips) (5); *Nautilus* (*Paracenoceras*) *hexagonus* Sow. (4) ... ... ca. 1 0

P. (*Arisphinctes*) *cotovui* (ool.) (J10,277)
cf. *cotovui* var. (ool.) (J10,283)
pickeringius (not coll.)
cf. *helenae* (J10,279)
cf. *vorda* var. (J10,273)
P. (*Kranaosphinctes*) *cymatophorus* (ool.) (J10,272, -82)
decurrens (J10,275)
Ochetoceras (*Campylites*) *henrici* (J10,261)

Berkshire Oolites:

6. Gritstone, blue-grey, hard, lumpy, impersistent, shelly ... 0 to 0 4

P. (*Arisphinctes*) *cotovui* (O.U. Dept. of Zool. coll.) *P.* (*A.*) *vorda* (J10,276)

?*vertebrale* Subzone	ft.	in.
5. Sand, yellow or khaki; *Ch. fibrosa* (Sow.) common	1	0
P. (*Arisphinctes*) *cotovui* (large body-chamber, not coll.) *pickeringius* (J10,278)		
P. (*Kranaosphinctes*) *cymatophorus* (J10,271) sp. nov. *G* aff. *decurrens* (not coll.)		
4. Gritstone, hard, grey, few fossils	1	0
3. Sand, cream, marly; *Exogyra* common	1	0
2. Rock, hard, not seen, *fide* foreman,	1–2 ft.	
1. Sand, 'considerable thickness'		

Another excavation 400 yards to the NW. (556034) (Fig. 2) showed 10 feet of yellow sand, with *Cardioceras excavatum*, immediately below a bed of gritstone, presumably equivalent to bed 2 or 4 in the above section.

Section (d)

Horspath Road, near Bullingdon Green.

New sections have come to light in pipe-trenches dug in connection with a new housing estate, and the Eastern By-pass road. They extended over considerable distances and allowed the lateral variation of beds to be followed.

(*i*) *Trench*, 300 yards due north of old Industrial School, 100 yards west of Industrial Schools North quarry, 200 yards south of the Horspath road (554044) (Fig. 2, and Fig. 4a, S. end).

	Osmington Oolites ft.	in.
7. Coral Rag and Wheatley Limestone: limestone rubble in brown and grey marl, with coral fragments ... seen	4	0
antecedens Subzone		
6. Limestone, grey, irregular, with lenticles of sand, passing locally into Shell Bed IV northwards	ca. 2	0
P. (*Dichotomosphinctes*) *antecedens* (J10,259)		
5. Sand, brown marly, with rubbly limestone lumps; profuse *Exogyra* and serpulae	0	6
	Berkshire Oolites	
4. Shell Bed III: limestone or gritstone, impersistent, nodular, a mass of fossils, notably *Gervillella*; dies out further to the north	0	6
P. (*Arisphinctes*) *pickeringius* (J10,260)		
?*vertebrale* Subzone		
3. Sand, yellow, marly, variable; passes northwards into sandstone and then Shell Bed II	6 in. to 1	0
2. Shell Bed I: limestone, grey, hard, gritty, flaggy, many fossils in south, passing into barren gritstone in north	1	0
1. Sand, yellow, even-bedded ... seen	4	0
A row of gritstone doggers 3 ft. down.		

The profile between this point and section (ii), near the road 200 yards due north, is shown in Fig. 4a.

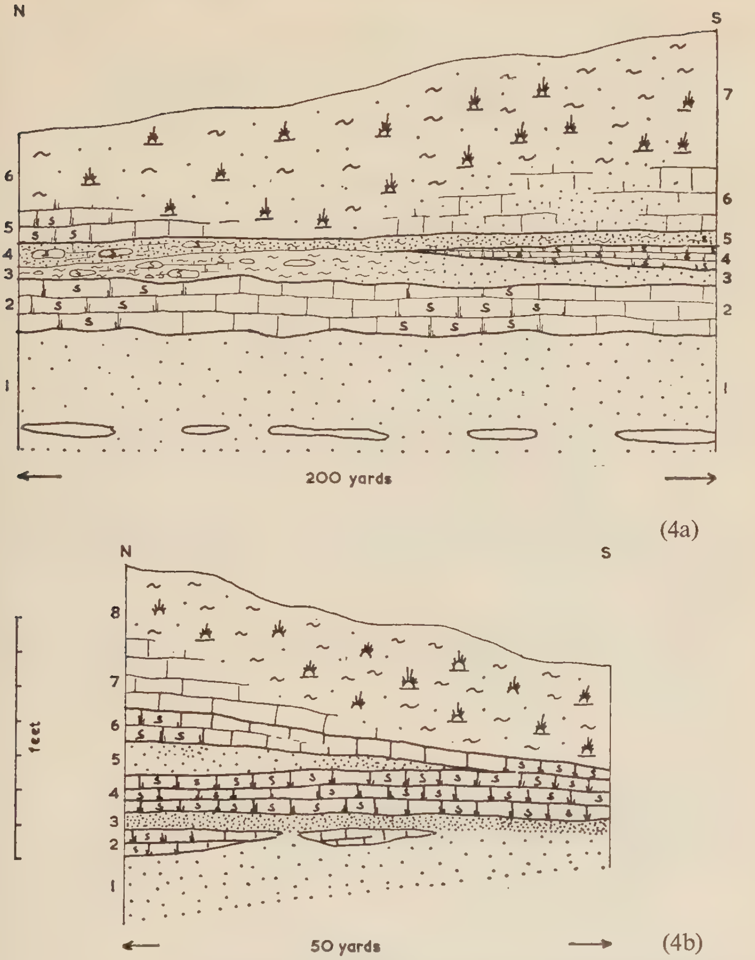


Fig. 4. Sections seen in trenches near Horspath Road and the Eastern By-pass, Cowley

(*ii*) *Trench* near Horspath Road at junction with road, 150 yards west of By-pass, and 200 yards north of section (i) (554046) (Fig. 2, and Fig. 4a, N. end):

Osmington Oolites	ft.	in.
6. Coral Rag and Wheatley Limestone: marly, rubbly limestone, some clay and sand ... ...seen to	2	0
5. Shell Bed IV: limestone, variable, as above but more massive; many shells, although locally unfossiliferous	0 to 1	0

Berkshire Oolites
ft. in.

4. Sand, brown, marly, with limestone lumps, or marly brown sandy limestone, locally Shell Bed III ... ... 0 4 to 0 8
C. (*Scoticardioceras*) *excavatum* (not coll.)

?*vertebrale* Subzone

3. Shell Bed II: sandy limestone, buff, marly, lumpy, locally nodular and a mass of fossils; replaces in part the bed above locally, and passes into sand southwards ... 0 6 to 1 0
P. (*Arisphinctes*) sp. seen
Aspidoceras perarmatum
2. Limestone, massive, grey, in places resembling the Natica Grits of Berkshire, unfossiliferous; but passing laterally into highly fossiliferous nodular, platy, Shell Bed I. ... 1 0 to 1 6
1. Sand, cream, even-bedded, with some shells ... ... seen 4 0
P. (*Arisphinctes*) sp., part of a large body chamber (not coll.)
A layer of impersistent gritstone, very hard, grey or blue-hearted, unfossiliferous, splintered into angular slabs, resembling true Lower Calcareous Grit, 3 ft. down in the sand ... about 0 8

(*iii*) *Trench* extending southwards along the new by-pass road; section at crossing of Horspath Road, 150 yards east of section (ii) (555046) (Fig. 2, and Fig. 4b, N. end):

Osmington Oolites

8. Coral Rag: rubbly limestone with some brown clay: a few corals, with serpulae, oysters, etc. ... ... about 3 0
passing into
7. Wheatley Limestone, rubbly ... ... 1 0 to 2 0

?*antecedens* Subzone

6. Gritstone, grey, massive, slabby, more or less fossiliferous, locally a Shell Bed III, upper surface brown 1 0
5. Sand, marly, compacted, brown 1 0
4. Shell Bed II: rubbly grey gritstone, a mass of fossils, especially *Gervillella* 1 0

Berkshire Oolites

3. Sand, marly, brown, many oyster fragments and Serpulae ... 0 6

?*vertebrale* Subzone

2. Shell Bed I: grey, discontinuous lenticular gritstone, locally a mass of fossils ... ... 0 to 1 0
1. Sand, cream, slightly marly ... ... seen 2 0

This succession changes rapidly: 50 yards to the south, bed 7 has merged into 8; bed 5 has disappeared; beds 4–6 have merged into a single Shell Bed, 1 foot 6 inches thick, with *P.* (*Liosphinctes*) *apolipon* (J11,920); bed 2 has disappeared, but beds 1 and 3 remain distinct. These changes are shown in Fig. 4b.

These sections lie not far from a number of old quarries now totally obscured, which in their day produced many ammonites. The most important were (Fig. 2):

(*iv*) *Horspath Road quarry*, just south of the road, 100 yards east of the by-pass (556045) (Buckman, 1925, 'sequence XI', 51; Pringle, 1926, 54) (see Fig. 3);

(*v*) *Brittledon Barn quarry*, in the NE. quadrant of the Horspath road–Roman road crossing, 200 yards east of (iv) (558045) (Buckman, 1925, 'sequence XII', 51);

(*vi*) *Industrial School's North quarry*, 200 yards SSW. of (v) (555043) (Arkell, 1927, 89);

(*vii*) *Industrial School's South quarry*, 300 yards south of (vi) (555040) (Arkell, 1936, 167; 1947, 93).

Although close together, the successions in these sections differed considerably, the total thickness of the beds between the Coral Rag above and the sands below, which include the so-called Cowley Shell Beds, varying from a few inches (v and vi) to about seven feet (iv and vii). Ammonites were recorded bed-by-bed from only one of them (iv); and the stratigraphical relation of the Cowley Shell Beds to the Headington Shell Bed farther north, and the Trigonia Beds of Berkshire to the west, were left in some doubt. The new sections show that in the Cowley area there may be in fact up to **four shell-beds in succession**; and that these may thin down and **fuse together into a single 'condensed' bed**, as found in Headington, without being cut out by a true unconformity.

3. PALAEONTOLOGICAL NOTES

It is now some ten years since Arkell's monograph on the Corallian ammonites was finished; and after applying the section dealing with the *plicatilis* Zone to the considerable material collected in recent years, a number of general conclusions may be briefly mentioned.

(a) Taxonomy

Arkell's units of taxonomic subdivision, i.e. the degree of 'splitting' into species, although at first glance perhaps somewhat formidable, seems fully justified (Arkell, 1935–48, 379–80). In the Perisphinctidae, the species appear to be more than the result of an arbitrary dissection into compartments of a highly but uniformly variable, genetically homogeneous population. The distinctions between species, at any rate as found in the limited region here considered, seem to be to at least some extent objective. Thus, of the new material from the *vertebrale* Subzone, by far the largest proportion could be accommodated in existing species, the cases in which a specimen appeared to be intermediate between two species, or belong to a new species, being very few. Arkell's description of the *vertebrale* Subzone fauna seems therefore reasonably complete.

As a result of the fine taxonomic scale which he adopted, Arkell was able to discern a considerable geographical factor in the composition of species and faunas, which, on a coarser scale, would have gone unnoticed (Arkell, 1935–48, 380). Similarly, it has now become clear that there are subtle changes of fauna with time, which can be made the basis of subzones of the *plicatilis* Zone; also, in contrast to the *vertebrale* Subzone, the new material from the *antecedens* Subzone contains a considerable number of previously undescribed species.

(b) Adult size

Arkell's remarks (1935–48, 379) concerning the general aspect of the fauna may be re-emphasised. The ammonites of the *plicatilis* Zone here considered form a classical example of what may, as on a previous occasion (Callomon, 1957, 61), be called a normal fauna. Leaving out of account all wholly septate material, by far the greatest proportion of specimens bearing some body-chamber is demonstrably adult, as diagnosed by approximation of the last few septal sutures, modification of the conch near the peristome and, in the Cardioceratidae, uncoiling of the umbilical seam. In fact, specimens which are, by the same criteria, demonstrably immature, are quite rare. As in other species, the maximum size of adults of any one species is well-defined. For example, in twenty-two adult specimens of *P.* (*A.*) *cotovui* (in O.U.M. or data from Arkell, 1935–48), sixteen were complete, and in fourteen approximation of sutures could be seen; the results were:

mean maximum size: 429 mm.; stand deviation 51 mm. = 12 per cent
mean diameter at
which septae cease: 300 mm.; stand deviation 37 mm. = 12 per cent

Similarly, in ten adults of *P.* (*D.*) *rotoides*

mean maximum size: 91.4 mm.; stand deviation 7.1 mm. = 8 per cent
mean diameter at
which septae cease: 61.2 mm.; stand deviation 4.9 mm. = 8 per cent

That comparable results apply to the other species too is apparent from Arkell's monograph. He himself stressed the adult maximum size as a specific character.

There occur cases where differences in adult maximum size are the only well-defined distinction between two species. Such a case has arisen in the interpretation of *P.* (*D.*) *antecedens*. This species, as defined by types, normally attains a maximum size of around 150 mm. There are found, however, shells which, as far as they go, are indistinguishable from *antecedens* in rib-curve, style of ornament and dimensions but which are fully grown and complete at about 90–100 mm. These small, *antecedens*-like forms are found in both *vertebrale* and *antecedens* Subzones, whereas the larger true *antecedens* appears to occur only in the *antecedens* Subzone and higher beds. The smaller forms may be incorporated in *P. rotoides* with no appreciable loss of precision; and in comparing *rotoides* with *antecedens* (as in Arkell's description of the species (1935–48, 91) the difference in sizes seems sufficient.

In marked contrast to the usual, normal fauna, there were found two cases in which the stone mould of the body-chamber of a normal ammonite contained a collection of small, complete but immature, Cardioceratids, between 10 and 30 mm. in size, and up to perhaps a dozen in number in each case. The first were found in *P.* (*A.*) *pickeringius* recorded from Woodperry Road quarry, Beckley, bed 1a (Callomon, 1953, 85; O.U.M. J6153); the second in *Goliathiceras* aff. *capax* at Cothill, bed 2 or 3 (author's collections, see below). They are too small for specific identification, but include more than one species. If they represented one or a number of successive broods, it is tempting to think that they were benthonic and gregarious, and that current action played little part in dispersal, either during life or after. This is also suggested by the peculiar distribution of *Aspidoceras* which is so common in the Cothill–Marcham area but rare a few miles away elsewhere, although the associated ammonite fauna is uniformly distributed; and the total absence of ammonites from the Coral Rag, although present in the immediately adjacent detrital Wheatley Limestone.

(c) Notes on various species

Complete descriptions of new species are beyond the scope of the present paper, and new names will not be introduced.

Genus **Perisphinctes** Waagen

To help in understanding the notes that follow, the classification of the main species (macroconchs only—see Callomon, 1955) may be briefly summarised. In the *vertebrale* Subzone, the commonest forms—what may be called the 'main stream'—fall into three groups when arranged in a sequence from the coarsest, sparsely ribbed to finest, most densely ribbed forms (excluding a few rare species):

1. *P.* (*Arisphinctes*) *maximus* — coarse
ingens
cotovui
pickeringius
cowleyensis
plicatilis — fine

2. *P.* (*Kranaosphinctes*) *decurrens* — coarse
kranaus
cymatophorus
trifidus — fine
3. *P.* (*Arisphinctes*) *kingstonensis*
vorda
helenae

(There is some doubt whether true *kingstonensis* occurs in the *Vertebrale* Subzone; its inner whorls are indistinguishable from those of *P. ingens*.) The species in each group have much in common: about the same maximum sizes, the same strengths of ribbing, modifying at about the same fairly late stage. At one extreme, *P. maximus* is transitional to *Perisphinctes* (*sensu stricto*); at the other, *P. vorda* is unusually smooth, already at early stages. Group 3 differs from group 1 by its consistent evoluteness. Standing well apart from the main stream are two isolated species, both rare:

P. (*?Kranaosphinctes*) *bullingdonensis*
P. (*Liosphinctes*) *cumnorensis*

The former has unusual ribbing on the outer whorls, but otherwise resembles the main stream. The latter is a small species—about half the size of the main groups—becoming very smooth at an early stage.

The main stream persists into the *antecedens* Subzone, but two additional groups appear; on the one side *Perisphinctes* (*sensu stricto*); on the other, joining on to *P. vorda*, a series of smaller, smooth species of the subgenus *Liosphinctes*.

Subgenus **Perisphinctes** (*sensu stricto*)

1. **Perisphinctes (Perisphinctes) chloroolithicus** (Gümbel)
Perisphinctes (*Perisphinctes*) *chloroolithicus* (Gümbel, Arkell, 1935–48, 95, etc.)

Remarks: two records from the *vertebrale* Zone of Beckley must be amended. (*a*) The specimen (J4250) listed by Arkell (1936) as *P.* (*P.*) *tumulosus* is an immature nucleus, maximum 90 mm., septate to 80 mm. Only two half whorls of ribbing being visible, it seems too poor to be even subgenerically identifiable. (*b*) The specimen recorded in Callomon, 1953 (Woodperry Road bed 1) is also a nucleus, which could perhaps equally well belong to *P.* (*A.*) *cotovui* as an inflated, rather involute variety.

For the present purpose it is essential to take into account only specimens which are identifiable beyond doubt. The above are the only examples of *Perisphinctes* s.s. recorded as from beds known to be of pre-*antecedens* age.

2. **Perisphinctes (Perisphinctes) de riazi** (Siemiradzki, 1899, nom. nov.)
= *Perisphinctes subrota* de Riaz, 1898 (non Choffat), 31, pl. xiv, from Trept.

Material: half an ammonite (J3856) from the Littlemore Clay Beds of Sandford (see above, p. 180).
Description: maximum size 220 mm., septate to ca. 200. The ribs have just started to modify into very swollen ridges after a deep constriction at 200 mm. Ribs on inner whorls typical of *Perisphinctes* s.s., up to ca. 60 per whorl at 130 mm.
Remarks: the holotype is imperfect and wholly septate, and but for this, as Arkell (1935–48, 109) remarked, the species might perhaps have been united with, taking precedence over, *P.* (*P.*) *parandieri* de Loriol 1903. The present specimen agrees with the Trept species very closely as far as it goes, and rather more closely than with *parandieri*, from which it differs in having a deep constriction at the point of modification, and ribs which modify even more abruptly.
Horizon: parandieri Subzone.

3. **Perisphinctes (Perisphinctes)** sp. nov. A

Perisphinctes sp. indet. Arkell (1935–48, 189, text-figure 29).

Material: one ammonite (O.U.M. J4330) labelled 'Marcham, Upper Trigonia Bed'.
Remarks: Arkell's original specimen (J4517) was from the Pusey Flags of Carswell Farm, wholly septate, maximum size 275 mm. The second specimen is also wholly septate, to 285 mm., and agrees with the first in almost every detail. The final septae are approximated in both specimens, but the body-chamber is still unknown. The ribs modify suddenly at 230 mm., giving the whole the appearance of typical *Perisphinctes* s.s., although the rib-curve is somewhat transitional to *Arisphinctes*.
Horizon: antecedens Subzone.

Subgenus **Arisphinctes**

4. **Perisphinctes (Arisphinctes) parandiformis** Arkell and sp. aff.

Perisphinctes (*Arisphinctes*) *parandiformis* Arkell (1935–48, 191, text-figure 67.

Remarks: the only specimens known previously were from the Highworth Grit of Stanford and the Pusey Flags of Carswell Farm. A third fragmentary specimen has now been found at Garsington Road substation; and a fourth specimen (J11,509) belonging to a very closely related species was obtained from a well-sinking near Stowford Farm, one and a half mile south of Beckley, in a preservation identical with that of ammonites from bed 10 at Beckley.

These species, by their general appearance, stand somewhat apart from the main stream, and seem in some ways transitional to *Perisphinctes* s.s. The new finds are from post-Vertebrale subzones, as probably are the original two.

5. **Perisphinctes (Arisphinctes)** sp. nov. **B**. aff. *vorda* Arkell cf. *Perisphinctes* (*Arisphinctes*) *vorda* Arkell, 1935–48, 154.

Material: one specimen from Cothill (Arkell coll., J4586), Upper Trigonia Bed, 8, by matrix.

Description: the specimen is complete at 210 mm., with degeneration of ribbing near the peristome and a broad, shallow constriction. It is septate to 135 mm. The ribbing and whorl-shape are exactly as in *P. vorda*; but no secondaries are visible at all where the venter first appears, at 130 mm. The species stands apart from the main stream in virtue of its small size.

Horizon: antecedens Subzone

6. **Perisphinctes (Arisphinctes)** sp. nov. **C**
P. (*Arisphinctes*) *ingens* (Y. and B.) Callomon, 1953, 84.

Material: one specimen (J6130) from Beckley, Woodperry Road quarry, Shell-Pebble Bed 2.

Remarks: the maximum diameter is 200 mm., and the general appearance of the ribbing and rib-curve seemed to resemble what could be seen of inner whorls of *P. ingens*. However, further cleaning showed the specimen to be complete and adult, with some degeneration of the last few ribs near the trumpet-like peristome, and approximation and degeneration of the final sutures. Four-fifths of the last whorl is body-chamber. The species is obviously a macroconch and belongs to *Arisphinctes* in the broad sense; yet a remarkable feature is the secondary ribbing, which is biplicate, with occasional intercalatories, up to a constriction at 150 mm., and thereafter weak but biplicate to the end.

Horizon: antecedens Subzone.

Subgenus **Liosphinctes**

Arkell (1935–48, lviii) originally questioned the value of keeping this subgenus separate from *Arisphinctes*. However, the new material justifies its retention, for the various species have a number of features in common which make them stand apart from the main stream: (a) they are on the whole smaller (200–300 mm.); (b) they have compressed outer whorls; (c) the ribbing is at all stages subdued, the modified primaries on the outer whorl turning into rounded nodes of low relief, concentrated near the umbilical margin, the secondaries fading altogether at already early stages; (d) different rib-curves; (e) septal sutures which tend to be simpler, less florid, with shorter lobes. In all, there is a resemblance to the later *Decipia* and *Pictonia*.

7. **Perisphinctes (Liosphinctes) laevipickeringius** Arkell
Perisphinctes (*Arisphinctes*) *laevipickeringius* Arkell, 1935–48, 42 and figures.

Remarks: there are transitions to *Arisphinctes* and the dividing-line is somewhat arbitrary. *P. laevipickeringius* was one of the species which did not fit easily into the main stream of *Arisphinctes* in Arkell's monograph; and it seems that it could more usefully be accommodated in *Liosphinctes*. There is certainly a strong resemblance to *P. apolipon*, as Arkell remarked, more so than to *pickeringius*; the holotype and paratype are both wholly septate (to 238 and 173 mm. respectively) but in both the final sutures are approximated, so that this is a small species compared with those of the main stream.

Both type specimens came from Industrial Schools Quarry, Cowley. Their preservation can now be identified as that of one of the higher sandy shell-beds, e.g. bed 7 of the Garsington Road section, or beds 5–6 of the section near Horspath Road (Fig. 4b). These are in the *antecedens* Subzone. The specimen from Horton Road, Beckley (Callomon, 1953) also came from this subzone.

The two specimens recorded by Arkell from Warboys, together with new and better material (Sedgwick Museum J20,268–70) have a certain resemblance to this species, but are not conspecific. In the author's opinion, the beds from which they came are not in the *plicatilis* Zone, but probably upper Praecordatum or lower Cordatum Zones. This is supported by a typical *Pavloviceras* (Sedgwick, J35,964) from the same beds.

8. **Perisphinctes (Liosphinctes)** sp. nov. **D**, aff. **laevipickeringius** Arkell.
Material: one ammonite (J3882), from Sandford sewage plant excavation, bed 4 or 5.
Remarks: maximum size 275 mm., septate to 250 mm. with approximation. Rib-curve, suture and style of ribbing similar to *laevipickeringius*; but somewhat larger, more compressed and evolute.

9. **Perisphinctes (Liosphinctes)** sp. nov. **E**, aff. **linki** Choffat
Perisphinctes sp. indet., cf. *linki* Choffat, Arkell, 1935–48, 189, text-figures 53 and 66.

Material: two ammonites (J3859, 3864) and fragments, from Sandford sewage plant excavation, bed 4 or 5.
Remarks: both specimens are adults, septate with approximation to 180 and 225 mm. respectively, and some body-chamber. They are without doubt specifically identical with Arkell's specimen from Kingston Bagpuize.

Choffat's holotype (pl. iv, fig. 1) is 153 mm. in diameter, but there is no indication whether any of it is body-chamber. A second specimen (Fig. 5) is septate to about 190 mm. Inner whorls agree well with the present species, but the outer whorls are much more densely ribbed.
Horizon: antecedens Subzone.

10. **Perisphinctes (Liosphinctes) apolipon** Buckman
Perisphinctes (*Liosphinctes*) *apolipon* S. Buckman, Arkell, 1935–48, 161, etc.

Material: three ammonites (J3860, –61, –95) from Sandford sewage plant excavation, bed 4 or 5, and various fragments.

Remarks: the first two of these differ somewhat from the holotype, the inner whorls being more densely ribbed. Besides the three English specimens described by Arkell and the three above, two others are known: G.S.M. SH4779 from Kingston Bagpuize (bed 6), and O.U.M. J6134 (Parker collection, 'Bullingdon pit'). Of these eight specimens, only those from Sandford carry any body-chamber; but in all of them the final septae are approximated. The mean diameter at which septation ceases in the adult is about 145 mm., and the maximum size is therefore around 200 mm., the species being a small one.

According to Buckman's original description, the holotype came from 'Cowley (near Industrial School), Brown Course', but Pringle (1926, 54) records it specifically as from his bed 6 of the Horspath Road quarry (*antecedens* Subzone). Parker's specimen is also in a matrix typical of this bed—stained red with rust and Serpula-encrusted—and thus probably a topotype.

11. **Perisphinctes (Liosphinctes)** sp. nov. **F**, aff. **apolipon**

Material: one complete adult (J3858) and fragments, from Sandford sewage plant excavation, bed 4.

Remarks: maximum size is 220 mm., septate, with approximation, to 145 mm. The ribbing resembles that of sp. *E* above, and is denser than in *apolipon*. The maximum size is closer to that of *apolipon*, however.

There is another similar specimen in O.U.M. from an old collection (J3854), and in exactly the same distinctive matrix as the above, which was labelled '*P*. aff. *linki* Choffat' by Buckman.

Subgenus **Kranaosphinctes**

12. **Perisphinctes (Kranaosphinctes) kranaus** Buckman

Perisphinctes (*Kranaosphinctes*) *kranaus* Buckman, Arkell, 1935–48, 174 and figures.

Remarks: previously, the only English specimen known was the holotype. A second good example has now been found at Cothill (Lower Trigonia Bed) agreeing well with the holotype in all respects and thereby helping to establish the individuality of the species. Its diameter is 340 mm., with the body-chamber just starting, and last few septae greatly approximated and degenerated. The size of the complete adult can thus be estimated to be about 500 mm.

13. **Perisphinctes (Kranaosphinctes) decurrens** Buckman

Perisphinctes (*Kranaosphinctes*) *decurrens* Buckman, Arkell, 1935–48, 175.

Remarks: the specimen listed from Garsington Road, bed 7 (J10,275), is not quite typical in that the ribbing modifies a little later. It shows, however, that the adult is septate to about 290 mm., which is normal for main-stream species, and that the species is not a small one as Arkell suggested. The ribbing on the outer whorls becomes extremely widely spaced on a highly depressed, flat-ventered whorl-section.

Another specimen worthy of note (G.S.M. 95043, from the Pusey Flags of Stanford in the Vale) is wholly septate, to 200 mm.; it is extremely evolute (umbilicus 60 per cent at already 140 mm. diameter), and the venter is completely smooth where first visible at 140 mm.

14. **Perisphinctes (Kranaosphinctes)** sp. nov. **G**, aff. **decurrens**

P. aff. *decurrens*, Arkell, 1935–48, 176, 178, pl. xxxix, fig. 6 only (B.M. no. 88655).

P. (*Kranaosphinctes*) sp. undescribed aff. *decurrens* (Buckman), Callomon, 1953, 85.

Remarks: this is a species at one extreme of the main stream; it differs from *P. decurrens* in being consistently even more inflated, more coarsely and less densely ribbed. The specimen from Woodperry Road quarry (holotype, J6011) is an adult, septate to 340 mm. The Steeple Ashton specimen, despite the aberrant nucleus, also belongs to this species. Parts of body-chambers have also been found at Beckley quarry (bed 8), and Garsington Road substation (bed 5), all in the same sandy matrix.
Horizon: vertebrale Subzone.

15. **Perisphinctes (Kranaosphinctes ?)** sp. nov **H**
Material: one ammonite (J3879) from Sandford sewage plant excavation, bed 5.

Description: the maximum size is 160 mm.; sutures are invisible, but part of the outer whorl appears to be body-chamber. Inner whorls are ribbed as in *P. cymatophorus*, but there is an abrupt modification at a deep constriction at 90 mm. The whorl-section swells suddenly, and the primary ribs become well-spaced low ridges which divide a little above half-way up the whorl-side into quintuplicate sheaves of secondaries. After another constriction at 130 mm. the venter is almost smooth. There is a strong resemblance to the much later genus *Rasenia*.
Horizon: antecedens Subzone

(d) The subzones of the Plicatilis Zone and their faunas

Three successive and somewhat different faunas among the ammonites of the *plicatilis* Zone can be recognised in the region under consideration. For reference, the standard successions will formally be taken to be those of Beckley, and the Marcham–Dry Sandford area; for these have produced more Corallian ammonites from accurately known horizons than any other.

Only a very few species are confined to a single subzone, the majority having a more extensive range. The faunal changes, perhaps not immediately obvious, are accentuated by considerable changes in relative abundance of genera. The ranges of the various elements of the faunas are shown in Fig. 5.

cordatum s.s.	*vertebrale*	*antecedens*	*parandieri*	Subzones
			———	*P.* (*Perisphinctes*) *parandieri*
		———	———	*chloroolithicus*
		———	———	*P.* (*Dichotomosphinctes*) *antecedens-buckmani*
		———	———	*C.* (*Maltoniceras*) *maltonense* and spp.
		———		*P.* (*Liosphinctes*) *laevipickeringius-apolipon* group
	———	———	– – –	*P.* (*Arisphinctes*) *cotovui* and *helenae* groups
	———	———		*P.* (*Kranaosphinctes*) *cymatophorus* group
	———			*P.* (*Liosphinctes*) *cumnorensis*
	———	———		*C.* (*Scoticardioceras*) *excavatum* group
	———	———		*C.* (*Cawtoniceras*) *cawtonense* group
———	———	———		*C.* (*Subvertebriceras*) *densiplicatum* group
———	———			*C.* (*Vertebriceras*) *vertebrale* group
———	———			*C.* (*Sagitticeras*) *moderatum* group
———	———			*Goliathiceras* (excluding *Pachycardioceras*)
———	———	– – –		*Aspidoceras*

Fig. 5. Zonal ranges of same ammonites

(*i*) *vertebrale* Subzone.

Perisphinctidae and Cardioceratidae occur in comparable numbers. None of the former is diagnostic, but among the latter, the strongly ribbed *Vertebriceras–Sagitticeras* and large inflated *Goliathiceras* (possible exception: one recorded by Arkell from the Urchin Marls of Highworth) appear absent from the higher subzones. The more compressed *Subvertebriceras* and others range upwards. *C.* (*V.*) *vertebrale* was already cited as diagnostic by Arkell.

Only a single *Aspidoceras* has so far been found in this country in Oxfordian definitely known to be higher than *vertebrale* Subzone, i.e. from Garsington Road substation (see above). (The specimen recorded by Pringle from Littlemore (see above, p. 181) is part of a *Perisphinctes*.)

It is very common in Berkshire, and Arkell suggested that it might form the basis of another subzone (Catena Subzone, Arkell, 1947), but further evidence makes it advisable to revert to his former view (1937, 448), and to regard this distribution as of strictly local significance.

(*ii*) *antecedens* Subzone.

The Perisphinctidae greatly outnumber the Cardioceratidae, which are comparatively rare. The subzone sees the appearance of the large *Dichotomosphinctes*, *D. antecedens* and *buckmani*; and on this Arkell's subzone was originally based. The smaller species, including *P.* (*D.*) *rotoides*, range up from below.

Perisphinctes (*sensu stricto*) seems also to commence in this subzone. The main stream of *Arisphinctes–Kranaosphinctes* is unchanged from below; it is joined, however, by various species of *Liosphinctes*.

Of the Cardioceratidae, the subgenus *Maltoniceras* seems to be the only new element in the subzone. The other forms are not diagnostic, or are insufficiently well known.

(*iii*) *parandieri* Subzone.

This is based on the faunas of the Wheatley Limestone and Littlemore Clay Beds of the Oxford district. Ammonites in these beds are rare, but enough have now been found to show that they make a distinct assemblage.

Localities	Beckley	Wheatley	Headington	Garsington Road	Sandford	Littlemore	Total
P. (*D.*) *buckmani*		1		1	2	4	8
antecedens			1	1			2
auriculatus		1					1
P. (*P.*) *parandieri/de riazi*	1	3		1		1	6
chloroolithicus	1			1			2
sp.		1				1	2
P. (*A.*) *cotovui*				2			2
cf. *parandiformis*				1			1
P. sp. fragments	4					2	6

(Details: Beckley: in Callomon, 1953. Wheatley: M.C.A.; and some additions: G.S.M. HBW1265, SH4781; O.U.M. J3850, J10,756. According to Mr. H. J. Hambidge, one of the Shell Beds was reached in the base of Lye Hill pit in about 1945, and produced *P.*(*A*). cf. *ingens* (J10,755) and *pickeringius* (J3853), which are in distinctive matrices. Headington: in M.C.A. Others, listed above; and J3417–18 from Littlemore)

Thus, of the thirty specimens known, all are Perisphinctids. The common small *P.* (*D.*) *rotoides* is absent. Among macroconchs *Perisphinctes* s.s. predominates, with *P. parandieri* new; but of the main stream only two specimens have been obtained. It is perhaps significant that the relative ranges of the *Arisphinctes–Kranaosphinctes* main stream, and *Perisphinctes* (*sensu stricto*), have an exact parallel in the relative ranges of *P.* (*D.*) *rotoides–ouatius* and *P.* (*D.*) *antecedens–buckmani.*

(*iv*) *General.* Division into subzones brings the *plicatilis* Zone more into line with the lower zones of the Oxfordian and the faunal changes proceed in a series of comparable steps.

Plicatilis	*Parandieri*
	Antecedens
	Vertebrale
Cordatum	*Cordatum*
	Costicardia
	Bukowskii
Mariae	*Praecordatum*
	Mariae

The faunas as found in this country are of course mixtures of those of two separate realms, the Tethyan (Perisphinctidae, *Peltoceras*, *Aspidoceras*, and Oppeliidae) and Boreal (Cardioceratidae); it is interesting to follow the local composition through the three zones. There is a gradual change from predominantly Boreal (*mariae* Zone) to exclusively Tethyan (*parandieri* Subzone) coinciding with the appearance of coral reefs, and hence signifying, with little doubt, a gradual change of climate. (Only a little later, in the *pseudocordata* Zone, Tethyan Perisphinctids are well-established in Greenland.) More remarkable, however, is the superimposed fluctuation in the relative proportions of the various Tethyan elements themselves: thus *Peltoceras* is common in the Praecordatum–Costicardia Subzones, *Aspidoceras* in the Costicardia–Vertebrale Subzones, yet *Perisphinctes* is rare in the Praecordatum–Cordatum Subzones. The Oppeliidae are relatively common in the Mariae Subzone, but then gradually recede from the region altogether.

The faunal differences between subzones are thus here, as elsewhere, partly ecological in origin, and there are therefore limits to the distances over which they might be expected to be recognisable. These distances are, however, not inconsiderable, for many of the subzones of the Oxfordian have been identified as far afield as southern Germany (Zeiss, 1957).

4. STRATIGRAPHICAL CORRELATIONS

The revised correlation of beds is shown diagrammatically in the Table, and the palaeontological evidence on which it is based is discussed below.

(a) Area I: Beckley (Fig. 3)

The succession in the three main quarries that have been described are readily correlated. Taken collectively, there are four successive faunas, which may be briefly outlined, including only those aspects relevant to the present discussion; all three subzones are easily recognised.

parandieri Subzone: Fauna IV—Wheatley Limestone
- *P.* (*P.*) *parandieri*
- *P.* (*P.*) *chloroolithicus*

antecedens Subzone: Fauna III—Shell-Pebble Bed
- *P.* (*P.*) *chloroolithicus*
- *Perisphinctes* main stream, 10 spp.
- *P.* (*L.*) *laevipickeringius*
- *P.* (*D.*) *antecedens*
    - *buckmani*
    - *rotoides*
- *Cardioceras*, 6 spp.

vertebrale Subzone: Fauna II—Beckley Sands (Beckley bed 8)
- *Perisphinctes* main stream, 5 spp.
- *C.* (*Vertebriceras*) *vertebrale*
    - (*Sagitticeras*) sp.
- *Cardioceras*, 5 spp.
- *Goliathiceras*, 2 spp.

Fauna I—(Beckley, bed 3; Woodperry Road, 1)
- *Perisphinctes* main stream, 9 spp.
- *C.* (*Vertebriceras*) *vertebrale*
    - *exaggeratum*
- *Cardioceras* sp.
- *Goliathiceras*, 2 spp.
- *Aspidoceras paucituberculatum*

In this area, the break between *antecedens* and *vertebrale* Subzones is marked by a well-defined unconformity (e.g. Arkell, 1936, pl. x, fig. 2).

(b) Area III: Cothill (Dry Sandford) (Fig. 3)

The section was described by Arkell (1936, 156) and many ammonites collected by him listed in the Monograph (1935–48). This magnificent quarry is now defunct, but in its last years it yielded much further material, now mostly in O.U.M. The complete faunal list, probably the most comprehensive of any Corallian exposure, seems worth recording: (WJA—Arkell coll. only).

(*bed* 10, Coral Rag)

antecedens Subzone: Fauna VI—*bed* 9, Urchin Marls (3 ft.)
- *P.* (*D.*) *gresslyi*

bed 8, Upper Trigonia Bed (4 ft.)
- *P.* (*D.*) *antecedens* (common)
    - (*P.*) *chloroolithicus*
    - (*A.*) *ingens* (WJA)
        - *cotovui*
        - *helenae* var.
        - sp. nov. *B* aff. *vorda* (WJA)
- *C.* (*Subv.*) *zenaidae* (WJA)
- *G.* (*P.*) *rhodesi* (WJA)

Correlation Table

<table>
<tr><th>Areas
Subzones</th><th>I
Beckley</th><th colspan="2">II
Headington–Cowley–Littlemore</th><th>III
Cothill–Marcham</th><th>IV
Kingston–Stanford–Faringdon</th><th>V
Highworth</th></tr>
<tr><td><i>Parandieri</i></td><td>Coral Rag and Wheatley Limestone</td><td colspan="2">Littlemore Clay Beds</td><td colspan="3">Coral Rag and Wheatley Limestone</td></tr>
<tr><td><i>Antecedens</i></td><td>Shell-Pebble Bed</td><td rowspan="2">Headington Shell Bed</td><td>Cowley–Sandford Shell Beds</td><td>Urchin Marls
Upper Trigonia Bed</td><td>Third Trigonia Bed
Highworth Grit and Clay
Pusey Flags
Upper Trigonia Bed</td><td>Highworth Grit and Clay
Urchín Marls
Highworth Limestones bed 8</td></tr>
<tr><td rowspan="3"><i>Vertebrale</i></td><td rowspan="3">Beckley Sands</td><td>Littlemore Shell Bed</td><td>Sand, bed 7
Lower Trigonia Bed
Sand</td><td>Pisolite</td><td>? bed 6</td></tr>
<tr><td colspan="2" rowspan="2">Sands</td><td colspan="3">Lower Calcareous Grit</td></tr>
<tr><td>Natica Band</td><td></td><td></td></tr>
</table>

vertebrale Subzone: Fauna V—*bed* 7, sand, even-bedded (2½ ft.)

P. (*A.*) *plicatilis* (? or *bed* 5)
(*K.*) *cothillensis* (? or 5, WJA)
cymatophorus
G. cf. *gorgon*
cf. *microtrypa*
elegans

C. (*Sc.*) *excavatum*
(*V.*) *vertebrale*
aff. *dorsale*
(*Sag.*) *moderatum*
cf. *cariniferum*

Fauna IV—*bed* 6, Lower Trigonia Bed (1 ft.)

P. (*A.*) *maximus* (WJA)
ingens
(*L.*) *cumnorensis* (WJA)
(*K.*) *cymatophorus*
kranaus
decurrens

C. (*Sc.*) *excavatum*
(*Subv.*) *densiplicatum*
(*Sag.*) *moderatum* (WJA)
G. *capax* (WJA)
gigas (WJA)
elegans (WJA)
A. *perarmatum* (WJA)
cf. *vettersianum* (WJA)

Fauna III—*bed* 5, sand, even-bedded (2½ ft.)

P. (*L.*) *cumnorensis* (WJA)
(*K.*) *cothillensis*
decurrens
C. (*Sc.*) *excavatum* (very common)
aff. *excavatum* (giant sp.)
delicatulum

G. aff. *capax*
A. *catena* (very common)
perarmatum
cf. *crebricostis*
paucituberculatum

—*bed* 4, gritstone (0 to 1½ ft.)

C. (*Caw.*) *intercalatum*

C. (*Subv.*) *densiplicatum*

Fauna II—Lower Calcareous Grit: *beds* 3, 2, sands and doggers, false-bedded (5 ft.)

C. (*Sc.*) *excavatum*
C. spp. nuclei
A. *catena*

G. aff. *capax*
G. *titan* (WJA)
A. *akantheen*

Fauna I—*bed* 1, Natica Band (5 ft.)

A. *catena*

The same succession as the above could be recognised bed for bed in the (now totally obscured) old Marcham Field quarry, three-quarters of a mile to the south (Arkell, 1936, 161), which yielded a very similar fauna. Fauna VI of Cothill corresponds to III in the Beckley area, V to II, and at least IV and III to I; whether Cothill faunas II and I are also incorporated in I at Beckley, or are without equivalent there, or even correspond to the Arngrove Stone, remains uncertain.

In the above account, the Lower Calcareous Grit has been taken to consist of from bed 3 downwards, restricting the use of the term to beds which are false-bedded with doggers (see discussion of this by Arkell, 1936), and excluding beds 4 and 5. Most of the famous examples of *Aspidoceras* with loosely-joined gas-chambers came from bed 5, in contrast with which ammonites in beds 3, 2 and 1 are quite rare.

A separate subzone for these lower beds rich in *catena* seems unjustified (suggested by Arkell, 1947, 98, but rejected by him 1937, 448; 1940, 1935–48, 201). The fauna known from the Natica Band of Cumnor, Cothill and Marcham is:

P. (*A.*) *cotovui*
  (*L.*) *cumnorensis*
C. (*Subv.*) *costulosum*
G. capax
A. catena (common)

typical of the *vertebrale* Subzone. Only the predominance of *catena* is unusual; but this is entirely local.

The succession has already considerably changed in Sheepstead Farm quarry, only half mile west of Marcham Field, one mile SW. of Cothill. This has recently been actively worked and showed a fine exposure (April 1958). Arkell has given a description (1947, 88) but the interpretation has to be somewhat revised. The Upper Trigonia Bed is correctly identified (*P.* (*D.*) *antecedens*, *P.* (*K.*) sp., and *C.* (*Maltoniceras*) cf. *vagum*, all in O.U.M.). However, the 'interlaminated sand and clay', bed 4, immediately below, is strongly false-bedded and almost unfossiliferous. It is the equivalent of beds 2 and 3 at Cothill, *not* 5, i.e. the Upper Trigonia Bed has come to rest directly on the Lower Calcareous Grit. There is thus a gentle unconformity here between the *antecedens* Subzone and the beds below, as at Beckley. The beds 2 and 3 at Sheepstead Farm, identified as the Lower Trigonia Bed, appear to be only a more calcareous development of the top part of the Natica Band. They are non-oolitic and only poorly fossiliferous, with no ammonites. The Natica Band (1c) itself has become discontinuous, changing laterally into sand.

(c) Area II: Sandford–Cowley–Headington

Having correlated the successions of areas I and III, it is now possible to return to the intermediate area II. The successions at Littlemore and Sandford readily fall into place, as indicated previously (p. 181, Fig. 3); the main Shell Bed in Littlemore railway cutting is the equivalent of beds 5–7 of Cothill (Lower Trigonia Bed); and the higher Shell Beds of the sewage plant excavation are the equivalent of the Upper Trigonia Bed. Thereafter, proceeding north-eastwards, the Lower Trigonia Bed is lost sight of as a coherent entity, its fauna being only recognisable here and there in Beckley Sand facies; the main shell-beds of Garsington Road and Cowley, of which there may be several in succession, are an expanded equivalent of the Upper Trigonia Bed. This correlation confirms Arkell's original interpretation of 1936 (169), but his table, 1947, 98, must be amended.

The *vertebrale* Subzone reappears in part as shell-bed in the old Horspath Road quarry (mentioned above, No. *iv*, p. 187, Fig. 3), for Pringle's bed 2 has yielded *C.* (*V.*) *vertebrale*, *dorsale* and *cowleyense* (with *P. kranaus*, *Cardioceras* 3 spp. and *Goliathiceras* in the sands below). Only 2½ feet separate bed 2 from the Wheatley Limestone above, with *P.* (*L.*) *apolipon* of the *antecedens* Subzone.

The new sections in Cowley have shown that these shell-beds can rapidly thin and fuse together. This provides the clue to the Headington Shell Bed: it is a 'condensed' deposit, the *vertebrale* and *antecedens* Subzones having joined together into a single homogeneous bed about a foot thick. It contains the faunas of both subzones in abundance, as shown in Arkell's table (1935–48, 392–3). Such a form of condensation would imply that the bed remained unconsolidated for a period equivalent in part to the deposition of both subzones. That something like this may have been possible is also indicated by the ammonites found in bed 7 of the Garsington Road section; some are preserved in dense white, coarse, oolite lying in yellow sand, such oolite being today unknown east of the Thames. It must have been formed without consolidation and later washed away to be replaced by sand, only such of it as penetrated into the shells of ammonites lying on the bottom being preserved. These shells are quite freshly preserved, and cannot be truly described as 'derived'.

(d) Area IV: Kingston Bagpuize–Stanford–Faringdon

The next section to be considered is that in the celebrated Lamb and Flag quarry, Kingston Bagpuize (Arkell, 1947, 87; now also totally defunct). The ammonite faunas are:

Bed 6: Trigonia Bed
    Perisphinctes main stream, 9 spp.
    P. (*L.*) *apolipon* (several)
        sp. nov. *E*, aff. *linki*
    C. (*M.*) *maltonense*
        (*Subv.*) sp. (= cf. *dieneri* Arkell)
Beds 5 and 4:
    Perisphinctes main stream, 2 spp.
Bed 3: Pisolite
    Perisphinctes main stream, 4 spp.
    Cardioceras, 1 sp.
    Goliathiceras, 1 sp.
    Aspidoceras, 1 sp.
(Lower Calcareous Grit below.)
Above the Trigonia Bed are the Pusey Flags, Highworth Clay and Grit.

The crux of the correlation lies in the age of the Trigonia Bed. Arkell assumed it to be the equivalent of the Lower Trigonia Bed of Cothill, although there was no positive evidence. According to the ammonites, however, as listed above, it is almost certainly the equivalent of the *Upper* Trigonia Bed: *Perisphinctes* greatly preponderates; and the two species of *Liosphinctes* indicate the *antecedens* Subzone as at Sandford-on-Thames sewage plant excavation. In contrast, the fauna of the Pisolite is typical of the *vertebrale* Subzone and Lower Trigonia Bed. Thus, in this interpretation, the Pusey Flags and Highworth Clay and Grit belong to the *antecedens* Subzone, and lie above the Upper Trigonia Bed.

Confirmation of this comes from the ammonites of the Pusey Flags themselves. A fair number are now known (O.U.M., G.S.M. and Sedgwick M.), mostly obtained from the Stanford quarries (29, 30 and 30A of Arkell's map, 1939, pl. 30; section, 1947, 86). They are

P. (*P.*) *chloroolithicus*	(several specimens)
sp. nov. *A*	(as in Upper Trigonia Bed, Marcham)
P. (*K.*) *decurrens* var.	(G.S.M. 95043)
P. (*D.*) *rotoides*	(several)
P. (*D.*) *antecedens*	(several)
C. (*Subv.*) *densiplicatum*	

an assemblage typical of the *antecedens* Subzone. The only ammonite known from the Highworth Grit, *P.* (*A.*) *parandiformis*, has otherwise also only been found in post-Vertebrale beds.

Yet another Trigonia Bed appears on top of the Highworth Grit in these quarries; Arkell called it the Upper Trigonia Bed, but to avoid confusion it may be better called the Third Trigonia Bed. It has here yielded no ammonites.

In the Shellingford cross-roads quarry, one and a half mile farther SW. (Arkell, 1947, 87), Coral Rag rests on up to six feet of oolitic limestones, one of them a Trigonia Bed ('Lower' was a misprint in Arkell's account), underlain by at least sixteen feet of highly false-bedded sand and interlaminated clay indistinguishable from typical Lower Calcareous Grit. Arkell thought this to be expanded Highworth Grit by extrapolation from the Stanford quarries, but this was always in some doubt (1939, 501); for just as, in this interpretation, these sands have doubled their thickness in a mile, they could equally well have wedged out, leaving the oolites resting on Lower Calcareous Grit.

This problem has now been resolved by the deep boring put down by the British Petroleum Company at a point one quarter mile WSW. of the quarry, 500 feet SW. of the cross-roads (Falcon, 1955). The following is a summary of the relevant part of the succession traversed in the bore-hole, made available through the kindness of Dr. Falcon:

	ft.	in.
Surface 298 ft. O.D.; derrick substructure 8 ft.		
Coral Rag and oolites: brown oolitic shelly limestone with grey-brown clay	8	0
Highworth Grit: 'buff clay'	6	0
Pusey Flags: grey oolitic limestone, shelly	ca. 20	0
Limestone, grey, oolitic, sandy in part	ca. 18	0
Lower Calcareous Grit: grey calcareous silt and silty sandstone with lignite	ca. 12	0
Silts, sands and sandstones	another 45	0
Oxford Clay below		

Total Corallian 109 feet; Lower Calcareous Grit 57 feet.

Arkell's interpretation is thus correct, and the sands in the quarry are Highworth Grit, with Pusey Flags below. The shell-bed below the Coral Rag is thus the Third Trigonia Bed, and has here yielded *P. antecedens* and *pickeringius*. The Upper and Lower Trigonia Beds, or their equivalents, may be represented in the sandy limestones below the Pusey Flags.

In the region of Faringdon itself, too few ammonites have been found to classify individual beds. However, most of the oolites, which become strongly developed here, belong to the *antecedens* Subzone, for *P. antecedens* is the commonest ammonite in them (M.C.A., Arkell, 1947, 85).

(e) Area V: Highworth

The main two quarries were described by Arkell (1927, 108, 111), who collected many ammonites from them. The succession is:

Coral Rag
Highworth Grit and Clay
Urchin Marls
Highworth Limestones
Lower Calcareous Grit

Almost all of the ammonites came from two distinct beds in the Highworth Limestone, beds 6 and 8, separated by a thin bed of marl or coralline rubble. The faunas quoted by Arkell are:

Bed 8: *Perisphinctes* main stream, 4 spp.
P. (*D.*) *antecedens*
rotoides
C. (*M.*) *maltonense*
highworthense
Bed 6: *Perisphinctes* main stream, 5 spp.
P. (*D.*) *magnouatius*
A. paucituberculatum (several)
Lo. Calcareous Grit:
Goliathiceras capax
?*Cardioceras* sp. (WJA 1927)
?*Aspidoceras* sp. (WJA 1927)

The matrices of the two limestone beds are indistinguishable, so that besides the above there is a considerable amount of further material, picked from piles of quarried stone, which could not be precisely placed (W.J.A., personal communication). Among this is quoted *P.* (*P.*) *chloroolithicus*. From the above lists it is clear that at least the upper of the two beds (8) represents the *antecedens* Subzone, equivalent to the Upper Trigonia Bed; and that here, the type-locality, as at Stanford and Kingston, the Highworth Grit and Clay are above the Upper Trigonia Bed. The position of bed 6 is not clear, although the presence of *Aspidoceras* suggests that it still belongs to the *vertebrale* Subzone, as does the top part of the Lower Calcareous Grit seen below.

(f) The Dorset Coast

Ammonites have been found in two groups of the relevant beds; the fauna is listed (Arkell, 1935–48, 386). Briefly:

Osmington Oolites:
  P. (*P?*) sp.
  P. (*A.*) *maximus*
  C. (*M.*) cf. *vagum*

Preston Grit:
  Perisphinctes main stream, 2 spp.
  Cardioceras, 5 spp.
  Goliathiceras, 2 spp.
  Aspidoceras, 3 spp.

Division into *antecedens* and *vertebrale* Subzones is therefore here also clearly recognisable.

(g) Cambridgeshire

The Elsworth and St. Ives Rocks contain the faunas of both *antecedens* and *vertebrale* Subzones, and seem to be condensed deposits of the same type as the Headington Shell Bed (see discussion, Arkell, 1937).

The fauna of the Upware Coralline Oolite is, however, quite different (listed in Arkell, 1937, 1935–48):

P. (*P.*) *parandieri*, *chloroolithicus* (several)
(*A.*) *maximus* (1)
(*D.*) *buckmani*, *antecedens* (common)
gresslyi
C. (*M.*) *maltonense* (common)
Cardioceras, 2 spp.
A. paucituberculatum (1)

It represents the *parandieri* Subzone, with perhaps traces of the *antecedens* Subzone. The exact positions in the succession from which the specimens came is unfortunately unknown; and the matrix of the *Aspidoceras* differs somewhat from that of the other specimens. (The *P.* (*A.*) *pickeringius* listed by Arkell (Sedgwick, J378) is a part of a *Perisphinctes* s.s. up to and including the point at which the ribbing is just modifying.) There is thus only a single specimen of the Perisphinctes 'main stream'. The Upware Coral Rag must therefore be a little younger than that of Oxford, as already suggested by Arkell on other grounds (1933, 417).

(h) Yorkshire

All the subzones are without doubt present, but not enough is known about the stratigraphic origin of the ammonites.

5. FACIES AND TERMS

Various aspects of lithology have in turn been emphasised at one time or other as being of special value in correlating beds; but as this paper has tried to show, the evidence of the ammonites suggests that beds of similar facies are by no means always of similar age. Thus, pebble-beds or lydites and quartz pebbles are found at various levels; shell-beds are highly variable and often localised; the presence or absence of Trigoniae is of only local significance, these ranging from the *Natica* Band (Sheepstead Farm) to the Third *Trigonia* Bed; corals are not confined to the Coral Rag but occur already in the *vertebrale* Subzone (Cothill and Highworth). All this is what might be expected in shallow off-shore deposits such as the Corallian beds.

Similarly, false-bedding in the sands, which were probably sandbanks sloping out to deeper water, seems to have depended more on position on the bank than time of deposition; for it is noticeable that at Beckley, near the eastern end of the bank, the sands are all evenly bedded; in the Marcham area they are false-bedded almost up to the first shell-beds, although at least the top part is of the same age as those at Beckley; and in the Stanford area even the Highworth Grit sands are strongly false-bedded, indistinguishable, but for the included doggers of oolite, from those of the Lower Calcareous Grit. This term has come to imply false-bedding as an essential ingredient, for it is all that distinguishes this type of deposit from the Beckley Sands, which have been regarded as distinct and included in the Berkshire Oolites (see Arkell, 1936, 169–70, for discussion).

Distinction between the terms Berkshire Oolites and Osmington Oolites is also somewhat obscure, either as pure facies terms or terms denoting age (see Arkell, 1947, 85); for the Upper Trigonia Bed has been placed in the latter, whereas both the Pusey Flags and Highworth Grit Clay have been put in the former. All these terms have been valuable in describing the field evidence in the absence of anything better; but it seems that where ammonites are available they are best no longer used.

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REFERENCES

ARKELL, W. J. 1927. The Corallian Rocks of Oxford, Berks and North Wilts. *Phil. Trans.*, **B216**, 67.

———. 1933. *The Jurassic System in Great Britain.* Oxford University Press.

———. 1935–48. A Monograph on the Ammonites of the English Corallian Beds. *Palaeontogr. Soc.* [*Monogr.*].

———. 1936. The Ammonite Zones of the Upper Oxfordian of Oxford, and the Horizons of the Sowerby's and Buckman's Types. *Quart. J. geol. Soc. Lond.*, **92,** 146.

———. 1937. The Zonal Position of the Elsworth Rock, and its alleged equivalent at Upware, Cambridgeshire. *Geol. Mag.*, **74,** 445.

———. 1947. *The Geology of Oxford.* Oxford University Press.

BUCKMAN, S. S. 1925. *Type Ammonites.* **5.**

CALLOMON, J. H. 1953. Sections in the Corallian Beds at Beckley, Oxfordshire. *Proc. Geol. Ass., Lond.*, **64,** 83.

———. 1955. The Ammonite Succession in the Lower Oxford Clay and Kellaways Beds at Kidlington, Oxfordshire, and the Zones of the Callovian Stage. *Phil. Trans.*, **B239,** 215.

———. 1957. Field Meeting in the Oxford Clay of Calvert and Woodham Brick Pits, Bucks. *Proc. Geol. Ass., Lond.*, **68,** 61.

CHOFFAT, P. 1893. Description de la Faune Jurassique du Portugal. Céphalopodes, 1: Ammonites du Lusitanien. *Trav. Géol. Portugal.*

COBBOLD, E. S. 1880. Notes on Strata exposed in laying out the Oxford Sewage Farm at Sandford-on-Thames. *Quart. J. geol. Soc. Lond.*, **36,** 314.

FALCON, N. L. 1955. The Faringdon Borehole. *Proc. geol. Soc. Lond.*, No. 1524, 93.

PRINGLE, J. 1926. The Geology of the Country around Oxford. *Mem. geol. Surv. U.K.* (2nd Ed).

RIAZ, A. de. 1898. *Description des Ammonites des Couches à Peltoceras transversarium* (*Oxfordian supérieur*) de Trept (Isère). Paris and Lyon.

ZEISS, A. 1957. Die ersten Cardioceraten–Faunen aus dem oberen Unter–Oxfordien Süddeutschlands und einige Bemerkungen zur Dogger/Malm–Grenze. *Geol. Jb.*, **73,** 183.

Summer Field Meeting at Ludlow

2–9 August 1958

Received 9 November 1959

Report by the Directors: R. ALLENDER, C. H. HOLLAND. J. D. LAWSON, V. G. WALMSLEY & J. H. McD. WHITAKER

THE MEETING was attended by about thirty-five members and one dog. Most of the party were accommodated in three hotels, the 'Cliff' (headquarters), the Guest House at No. 2 Dinham, and the 'Ludlow Arms'. Coach transport was provided both economically and efficiently by the Corvedale Motor Company Ltd., Fishmore Road, Ludlow. The secretary for the excursion was Mr. W. D. I. Rolfe.

On the first evening (Saturday, 2 August) the organising director (Dr. J. D. Lawson) gave an introductory talk on the scope of the week's excursion. He emphasised that it differed from the more familiar South Shropshire itineraries in concentrating attention on the higher Silurian rocks which had been intensively studied in recent years by the Ludlow Research Group. In case these variations on one theme might prove monotonous for some of the party, visits to exposures of Pre-Cambrian, Cambrian, Ordovician, Old Red Sandstone and Pleistocene deposits had been included.

In the area studied there are continuous outcrops of Wenlockian and Ludlovian rocks belonging to two main facies: the thinner and more calcareous shelf facies and the thicker and less calcareous basin facies, in which slumped beds commonly occur (Lawson, 1956). The distribution of these contrasting developments is shown on the index map (Fig. 1), together with the areas visited. The change in the geological facies is strikingly reflected in the character of the scenery. Over the shelf area the limestone formations give rise to conspicuous wooded scarps separated by broad valleys eroded in the mudstones. The less calcareous and predominantly silty rocks of the basin facies result in pastoral upland and moorland with deep valleys. The organising director also tried to persuade the party that the sun always shines on the shelf whilst it rains in the basin.

One purpose of this field excursion was to demonstrate the need for a revised classification of the Ludlovian rocks of the type area. This new scheme has now been published (Holland, Lawson & Walmsley, 1959) but is tabulated in Fig. 2 which also shows the equivalent formations in the previous classification and the probable correlation with the basin successions. The divisions are defined primarily on faunal assemblages and are applicable, in spite of many local variations, over the whole of the shelf area. Descriptive names, based on a common fossil or lithological character (e.g. *Dayia* Shales), have been deliberately avoided because the description, although very apt in one area, may make the name unusable in a different but contemporaneous facies. As will be seen from Fig. 2, most of the divisions correspond to formations previously recognised but there are two important exceptions. The Lower Bringewood Beds are calcareous siltstones with a fauna of large brachiopods (including *Strophonella euglypha*, *Strophonella funiculata*, *Brachyprion sp. nov.* and *Gypidula lata*) but without the compound corals and stromatoporoids which characterise the limestones of the Upper Bringewood Beds. These beds reach a thickness of over 200 feet but it is not easy to decide where they fit into the old classification as they cannot be correctly mapped as Aymestry Limestone

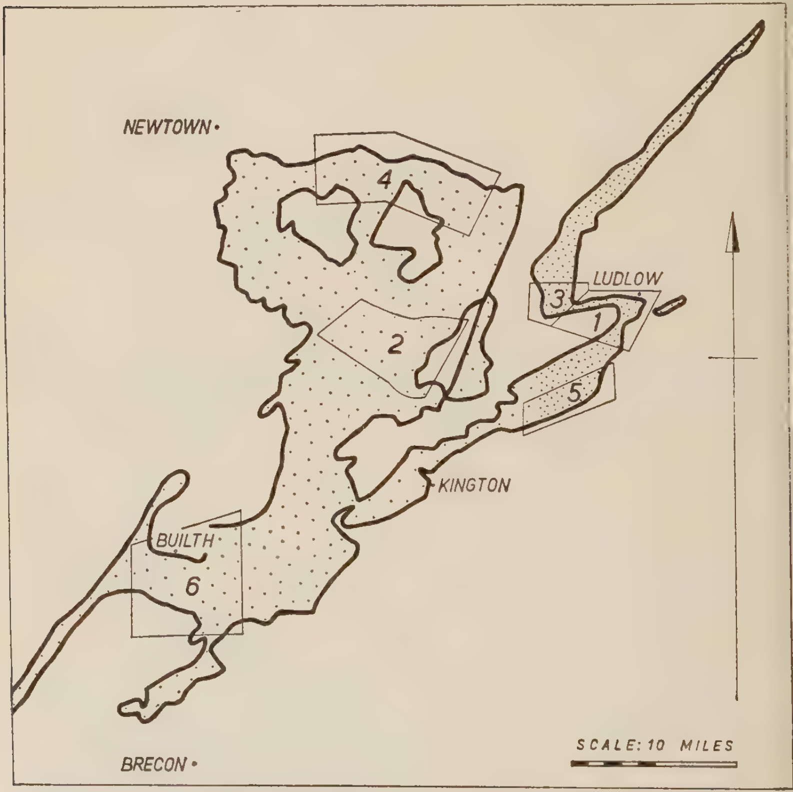

Fig. 1. The above map shows the outcrop of Ludlovian rocks in the Welsh Borderland, with the shelf facies indicated by the fine stippling and the basin facies by the coarser ornament. The areas visited are numbered in the excursion order as follows: (1) Ludlow, (2) Knighton, (3) Leintwardine, (4) Bishop's Castle, (5) Aymestrey and (6) Builth

BUILTH	KNIGHTON	BASIN DIVISIONS	GRAPTOLITIC ZONES	LUDLOW New classification	LUDLOW Old classification
HOLOPELLA BEDS	LLAN-WEN HILL BEDS	UPPER LUDLOW SHELLY SILTSTONES 500—1650 ft.		UPPER WHITCLIFFE BEDS 100 ft.	CHONETES BEDS
C. STRIATELLUS BEDS				LOWER WHITCLIFFE BEDS 80 ft.	RHYNCHONELLA BEDS
TRANSITION BEDS	WERN QUARRY BEDS				
C. GRAYI BEDS	KNUCKLAS CASTLE BEDS	LAUENSIS BEDS 250 ft	*M. leintwardinensis*	UP. LEINTWARDINE BEDS	? DAYIA NAVICULA BEDS
LINGULA LATA BEDS	BAILEY HILL BEDS	LEINTWARDINENSIS BEDS 300-650 ft.		LR. LEINTWARDINE BEDS 100 ft.	
		LOWER LUDLOW SHELLY SILTSTONES 2,000-3,000 ft.	? *M. tumescens*	UPPER BRINGEWOOD BEDS 40-150 ft.	AYMESTRY LIMESTONE
"ATRYPINA" BEDS					
PTERINEA TENUISTRIATA BEDS				LOWER BRINGEWOOD BEDS 150-200 ft.	
				UPPER ELTON BEDS 150-250 ft.	? LOWER LUDLOW SHALES
CYRTOCERAS MUDSTONES					
			M. scanicus	MIDDLE ELTON BEDS 150-300 ft.	
GRAPTOLITIC SHALES	LOWER LUDLOW GRAPTOLITIC SHALES	LOWER LUDLOW GRAPTOLITIC SHALES 600-800 ft.			
			M. nilssoni		
			? *M. vulgaris*	LOWER ELTON BEDS. 100-150 ft.	

Fig. 2. Correlation chart for the Ludlovian Rocks of the Welsh Borderland

or *Mongraptus tumescens* Flags. The Upper Leintwardine Beds have also not been previously recognised even though the fauna is most distinctive and invaluable for inter-facies correlation; the division is only about twenty feet in thickness. It is characterised by an overlap of the *Dayia navicula* and *Chonetes striatellus* faunas as described by Straw (1937, 411–12) and by the occurrence of *Beyrichia lauensis* and *Calymene neointermedia*, restricted to this division. The faunal lists of Elles & Slater (1906) suggest that they included these beds in their Dayia or Mocktree Shales division. The stratigraphical term 'Aymestry Limestone' is to be abandoned for this general classification, not merely because the conventional geological spelling differs from that of the village of Aymestrey but because the name has been applied by many geologists to any limestone within the Aymestry group of Elles & Slater (1906). Along Wenlock Edge and in the south-eastern inliers the calcareous equivalents of the *Dayia* or Mocktree Shales (the Lower Leintwardine Beds of this classification) have often been called Aymestry Limestone.

Although there are many separate classifications, using local or fossil names, for areas in the basin facies of the Ludlovian it is now possible to unite them in a scheme of five divisions to cover the central Wales and Welsh Borderland region. This classification is briefly defined below.

5. Upper Ludlow Shelly Siltstones characterised by the dominance of the *Chonetes striatellus* fauna.
4. *Beyrichia lauensis* Beds characterised by an overlap of the *Dayia navicula* and *Chonetes striatellus* faunas and acmes of *Beyrichia lauensis* Kiesow, *Chonetoidea grayi* (Davidson) & *Calymene neointermedia* R. & E. Richter.
3. *Leintwardinensis* Beds: about 500 feet characterised by acmes of *Monograptus leintwardinensis* Lapworth, and *Lingula lata* J. de C. Sowerby.
2. Lower Ludlow Shelly Siltstones; a thick group (2000–3000 feet) consisting mainly of siltstones with a predominantly benthonic shelly fauna but with spiny Monograptids fairly common. There is considerable variation in lithology and fauna both laterally and vertically.
1. Lower Graptolitic Shales, about 750 feet of graptolitic shales of the zone of *Monograptus nilssoni*, extending into the Zone of *Monograptus scanicus* above, and in the Bishop's Castle area, into the *Monograptus vulgaris* Zone below.

Sunday, 3 August

Director: V. G. Walmsley

Ludlow area (Ordnance Survey one-inch map 129; 1/25,000 maps SO/47, SO/57). The main purpose of this first day's excursion was to demonstrate the validity of the new classification scheme (Holland, Lawson & Walmsley, 1959) by examining all the divisions in ascending order along the Wigmore road.

The party travelled by coach about four and a half miles on the Wigmore road from Ludlow to an excellent view-point (456714)[1] on the axis of the denuded north-easterly pitching Ludlow anticline, and the topographic expression of the Wenlock and Ludlow rocks was pointed out as a preliminary to the traverse along the axis. The route was then retraced across Wenlock Shale ground to Pitches Coppice (470729) where the coach was dispensed with and the rest of the day was spent on foot.

The topmost Wenlock Shale, poorly exposed at Pitches Coppice, passes up gradually into the Wenlock Limestone which is more flaggy and argillaceous and much less fossiliferous than on Wenlock Edge. In a roadside quarry (47077302) several brachiopod species (*Atrypa reticularis* (Linnaeus), *Rhipidomella hybrida* (J. de C. Sowerby), *Eospirifer* sp. and *Sowerbyella* sp.) and some reddened tubular bryozoa were collected from the flaggy marlstone development. The highest Wenlock Limestone is very nodular and was examined in an old quarry a few yards south of the road (47257300), where the sharp junction with the overlying Lower Elton Beds was also seen. These latter beds are soft greenish-grey shales speckled with white shell fragments. The gradual onset but sudden termination of the limestone phase and the problem of correlation of the Wenlock Limestone were discussed.

The party then walked across to a small stream exposure in the Middle Elton Beds (47857328). These blue-grey soft soapy shales yielded *Chonetoidea grayi*, *Dalmanites vulgaris* (Salter) and small nautiloids, but the characteristic graptolites of the *Monograptus nilssoni-M. scanicus* assemblage proved difficult to find. At Gorsty Farm (47857355) a roadside exposure of Upper Elton Beds (flaggy olive-green siltstones) yielded many good specimens of *Monograptus tumescens* Wood and rare specimens of *Brachyprion* sp. nov. The succeeding flaggy but more calcareous siltstones of the Lower Bringewood Beds (previously included in the Aymestry Limestone) were examined in a roadside quarry (48257373) from which *Leptaena rhomboidalis* (Wilckens), *Brachyprion* sp. nov. and *Lingula* sp. were collected. Graptolites were notably scarce. Leaving the road by the field gate immediately east of Mary Knoll House, a track was followed to the quarry (48517370) at the north end of Mary Knoll. Here tough nodular limestones and calcareous siltstones of the Upper Bringewood Beds yielded a typical Aymestry Limestone fauna including *Atrypa reticularis*, *Leptaena rhomboidalis*, *Strophonella euglypha* (Hisinger), *Conchidium knightii* (J. de C. Sowerby), compound corals and fragments of crinoids and bryozoa. Lunch was taken, between showers, on the top of Mary Knoll whilst appreciating the panoramic view which embraced the Longmynd, Wrekin, Clee Hills, Abberley Hills, Malverns, Woolhope, Black Mountains and Radnor Forest in clockwise order.

Returning to the road, the party followed the Forestry Commission track which runs from Gorsty Farm, westwards across the dip slope of Bringewood Chase, to visit the excellent exposure of Upper Bringewood Beds created by a large landslide (47307379). Here the distribution and orientation of the typical fossils *Strophonella euglypha*, *Atrypa reticularis* *Gypidula* sp., *Dalmanella orbicularis* (J. de C. Sowerby) and *Favosites* sp. were seen on a wide expanse of bedding plane. The return journey to Gorsty Farm afforded good views of Corve Dale, the Onibury gap and the Longmynd. Continuing the road journey to Ludlow, the higher Ludlovian formations were examined in turn at a series of roadside exposures. At the first of these (48707385), the succession was picked up again by examining nodular limestones of the Upper Bringewood Beds from which typical fossils including *Conchidium knightii* were collected. Slightly higher beds exposed in the next (and largest) quarry (48877389) aroused much interest because their calcareous lithology has resulted in their misidentification as Aymestry Limestone. The fauna of *Dalmanella orbicularis* (very common), *Chonetes lepisma* (J. de C. Sowerby), *Sphaerirhynchia* (*Wilsonia*) *wilsoni* (J. Sowerby), and *Dayia navicula* (J. de C. Sowerby) clearly indicates that these are Lower Leintwardine Beds of a calcareous facies.

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[1] All National Grid References lie in the 100 km. square 32 (SO).

In the topmost Lower Leintwardine Beds, examined in a deep roadside quarry (49107399), this assemblage was joined by *Shaleria* (*Brachyprion*) *ornatella* (Davidson), and *Fuchsella* (*Orthonota*) *amygdalina* (J. de C. Sowerby). The succeeding Upper Leintwardine Beds, with their characteristic fauna of *Chonetes striatellus* (Dalman), *Dalmanella lunata* (J. de C. Sowerby) and *Camarotoechia nucula* (J. de C. Sowerby), (these three being more common in the succeeding beds), *Dalmanella orbicularis* and *Shaleria ornatella* (both common also in the beds below), *Beyrichia lauensis* and *Calymene neointermedia* (both confined to these beds) were seen in a small quarry (49257406). The correlation value of this horizon, not previously described from the Ludlow area but now known to be widespread in the Welsh Borderland, was pointed out. Lower Whitcliffe Beds (poorly bedded calcareous siltstones), with *Chonetes striatellus*, *Dalmanella lunata*, *Camarotoechia nucula*, *Fuchsella amygdalina* and *Serpulites longissimus* J. de C. Sowerby, were examined in another roadside quarry (49407416) and the party then moved quickly over unexposed Whitcliffe Beds to the junction of Ludford Lane and the main Ludlow–Leominster road (51177413). Here the classic section, which includes the top few feet of the Whitcliffe Beds, the Ludlow Bone Bed and the overlying Downton Castle Sandstone, was examined and some aspects of the Silurian–Devonian boundary problem were discussed.

Finally the party descended the path to the River Teme, noting on the way exposures of Upper Whitcliffe Beds and the contorted beds at the top of the Lower Whitcliffe division (50957415). Moving northwards along the river bank towards Dinham Bridge, the lowest beds exposed (50757427) in the dissected nose of the pitching anticline were examined. They have previously been considered as Aymestry Limestone but careful examination of the fauna has now shown that even the lowest strata are Lower Leintwardine Beds and this is confirmed by the close proximity of the overlying Upper Leintwardine Beds. The misleading appearance of the lithology and the value of studying the total fossil assemblage were discussed. Members then returned on foot to their respective hotels.

Monday, 4 August

Director: C. H. Holland

Knighton area (Ordnance Survey one-inch maps 128, 129, 1/25,000 maps SO/26, SO/27, SO/36, SO/37). The greater part of the day was devoted to the thick Ludlovian sequence of basin facies, though the lower Downtonian rocks received brief attention in the late afternoon. The succession of strata in the area is as follows (Holland, 1959):

9. Red Downtonian	at least 2000 feet
8. Green Downtonian	50–300 feet
7. Yellow Downtonian	25–35 feet
6. *Platyschisma helicites* Beds	20–40 feet
5. Llan-wen Hill Beds	500 feet
4. Wern Quarry Beds	120–170 feet
3. Knucklas Castle Beds	1500 feet
2. Bailey Hill Beds	about 3500 feet
1. Lower Ludlow Graptolitic Shales	at least 750 feet

The less fossiliferous, monotonous greyish siltstones of the Ludlovian provided a striking contrast to the more varied rocks examined during the previous day's traverse of the Ludlow Anticline.

The route lay westwards along the Teme Valley. A halt was made at a point (35037260) half a mile east of Heartsease Farm, where a roadside sign welcomed the party to Wales. The Director pointed out the wooded feature made by the Upper Ludlovian and the effect upon this of several faults associated with the Church Stretton disturbance. The coach now proceeded through Knighton to Heyop, where a narrower road was negotiated to Upper Hall Farm. From here the party continued on foot under the railway arch and up the track to the old quarry (22527482), where the middle Bailey Hill Beds, dipping steeply to the north-west and showing minor folds and faults, are well displayed.

The typical lithology of the Bailey Hill Beds (the greater part of which make up the Lower Ludlow Shelly Siltstones in the Knighton district) is of shaly and flaggy siltstones with prominent bands of well-jointed, flaggy or massive, calcareous siltstones which often show internal contortions. Bands of comminuted shells, especially rich in *Dalmanella orbicularis* are characteristic of the middle part of the group and specimens of these were collected.

Leaving the coach again at Heyop School, the party ascended the lane south-westwards towards the higher ground of Bailey Hill (accessible by car). At the top of the lane (22987292) mist somewhat obscured the view, but the Director commented upon the characteristic ridge and valley topography of this western part of the district, and its relationship to a belt of disturbance of Caledonoid direction. The route now lay along the lane eastwards for some 250 yards, across fields, and finally down into the bracken-covered dingle of Cwm Jenkin. Here (23537297) upper Bailey Hill Beds were examined in the sides and course of the stream. A good collection of shelly fossils included *Sphaerirhynchia wilsoni*, *Dayia navicula*, and *Camarotoechia nucula*. The graptolite *Monograptus chimaera* Barrande var. *semispinosus* Wood was found to be common.

From here the party climbed the western side of the valley to an exposure (23537318) near the top of the Bailey Hill Beds. The uppermost hundred feet or so of this formation consist of smoothly bedded, more or less striped, shaly and thin flaggy siltstones. Shelly fossils are now rare but specimens of the only remaining graptolite, *Monograptus leintwardinensis*, were obtained. The Director pointed out the importance of this horizon (the *Leintwardinensis* Beds of the basin facies) as a link between basin and shelf. The succeeding lower Knucklas Castle Beds were seen in a smaller exposure some fifty yards to the north-north-east. The lithology was the same but the beds were now unfossiliferous. This was probably the horizon in other more favourable areas of the important *Beyrichia lauensis–Chonetoidea grayi* fauna, which had not as yet been seen in the Knighton district. The return was made to Heyop, and thence by coach to the inn at Knucklas.

After lunch the party motored towards Knighton and then south-westwards along the main Penybont road. A roadside exposure (24747020) showed upper Knucklas Castle Beds, the lithology being the same as that seen at the last locality. At this low level of the Upper Ludlow Shelly Siltstones a few typical Upper Ludlovian forms such as *Serpulites longissimus* make their appearance. They are, however, very rare, and a brief visit was insufficient to produce any specimens. The next exposure to be visited was the large old quarry in Wern Quarry Beds (24957040), about 350 yards back along the road. The lithology is of massive or thick flaggy siltstones, typically irregularly bedded. In these beds the Upper Ludlovian fauna is gathering strength and members soon assembled a collection of typical forms such as *Fuchsella amygdalina*, *Camarotoechia nucula*, *Chonetes striatellus*, *Orbiculoidea rugata* (J. de C. Sowerby) and *Serpulites longissi-*

mus. The Director commented upon the resemblance between these beds and the Lower Whitcliffe Beds of the Ludlow Anticline.

The coach now proceeded to Monaughty and hence along the Lugg Valley. The feature made by the Upper Ludlow Shelly Siltstones rises steeply from the valley and beyond Whitton the coach climbed northwards on to the summit ground capped by the gently dipping Llan-wen Hill Beds of the central part of the district. A brief pause having been made at the point (28256886) where Offa's Dyke crosses the Presteigne road, the next exposure to be visited was an old quarry in Llan-wen Hill Beds (29526866). Here the flaggy and shaly siltstones yielded a fully developed Upper Ludlovian fauna, including especially *Dalmanella lunata*, *Chonetes striatellus* and *Camarotoechia nucula*.

The coach now returned to the road junction (28166972) previously passed and from here the party made a traverse on foot across the top of Llan-wen Hill. The ground is poorly exposed but provides extensive views towards both Knighton and Presteigne. The last exposures to be examined were along the more or less continuous section provided by Meeting House Lane, which runs southwards from the summit track of Llan-wen Hill (30096993). The section shows uppermost Ludlovian rocks followed by the lowest Downtonian. Within the latter, the *Platyschisma helicites* Beds, with their shell bands of *P. helicites* (J. de C. Sowerby) and *Modiolopsis complanata* (J. de C. Sowerby), are succeeded firstly by massive, yellowish, coarse siltstones of the Yellow Downtonian and then by the blocky fracturing olive siltstones of the Green Downtonian. The characteristic red soils of the Red Downtonian outcrop could be seen beyond. The Ludlovian–Downtonian boundary crosses the lane at a point (30226940) about 120 yards north-west of Meeting House Farm. Two notable finds were made by members of the party during the examination of this section. Firstly, *Howellella elegans* (Muir-Wood) (*Spirifera elevata* mut. in Elles & Slater, 1906), previously unrecorded from the Llan-wen Hill Beds of the district, was found, as at Ludlow, to be present in the uppermost few feet of the Ludlovian. Secondly, within the *Platyschisma helicites* Beds, Mr. C. O. Baker discovered a thin layer of bone-bed with Thelodont denticles, recalling the Downton Bone Bed of the Ludlow District and the occurrences at a corresponding position in the Bishop's Castle succession, recently investigated by Mr. R. Allender.

The party now regained the summit track and continued north-eastwards to Llanshay Lane. From the lane (30907062) a splendid view was obtained of the eastern part of the district with the Leintwardine area and the Ludlow Anticline seen beyond. The details of the view were explained and the changing pattern of sunlight and shadow illuminated the various features. The coach was waiting at the foot of Llanshay Lane (29407203) and the party made a somewhat late return to Ludlow.

Mrs. Leach kindly made available the lounge at the 'Ludlow Arms' for the evening and Mr. Whitaker gave an introductory talk on the Leintwardine area illustrated by coloured slides.

Tuesday, 5 August

Director: J. H. McD. Whitaker

Leintwardine area (Ordnance Survey one-inch map 129, 1/25,000 map SO/47). Leintwardine lies some six miles west of Ludlow and a similar distance east of Knighton and this intermediate position between shelf and basin facies is reflected in the lithology and fauna of the rocks of the Leintwardine area, which range from Wenlock Shale to Old Red Sandstone. The succession is similar to that of the Ludlow area shown in Fig. 2 but there are important differences in lithologies, faunas and thicknesses.

Some of the divisions attain a much greater thickness than at Ludlow, e.g. the Lower Leintwardine Beds (up to 350 ft.) and the Whitcliffe Beds (about 500 ft.). On the other hand, there are places where the Upper Elton Beds and the Bringewood Beds are completely cut out by local unconformities.

Shelf conditions are shown by the presence of the Wenlock and Upper Bringewood limestones and the very fossiliferous basal strata of the Lower Leintwardine Beds; basin conditions by the higher strata of the Lower Leintwardine Beds (with *Monograptus leintwardinensis* and *Lingula lata*) and the Upper Leintwardine Beds (with *Chonetoidea grayi*, *Beyrichia lauensis* and *Calymene neointermedia* and the scarcity of *Shaleria ornatella*). The siting of the Leintwardine area near the junction of the continental shelf and continental slope during most of the Ludlovian epoch is further supported by evidence of 'slumping' at seven horizons and the presence of six parallel channels cut and filled during Lower Leintwardine times, one of which—the Church Hill channel—has already been described by Alexander (1936). The writer interprets these as the upper reaches of submarine channels similar to those which lie between the submarine canyons of the present day. Whether any of them are Ludlovian representatives of full-scale canyons is difficult to ascertain from the limited exposures around Leintwardine; the writer's mapping in the Wigmore–Lingen area may help to decide this point. The channels all trend to west-south-west from shelf to basin, their courses being in part controlled by contemporaneous faulting.

Travelling by coach from Ludlow along roads A49 and A4113 the party reached the Quarry Plantation one and a half miles west-south-west of Bromfield (45267602). Here, very micaceous flaggy and cross-bedded sandstones with a minor slump horizon were seen, these beds being highest Downton Castle Sandstone. Walking 1000 yards westwards along the main road the party next examined lowest Downton Castle Sandstone which appears on the north side of the road (44397589). This soft, fine-grained sandstone, from which *Lingula* sp. and *Kloedenia wilckensiana* (Jones) were collected, has small-scale slumping at its base and rests directly on the *Platyschisma* Bed which in turn overlies Upper Whitcliffe Beds. The Ludlow Bone-Bed does not appear to be developed. The Upper Whitcliffe Beds are continuously exposed along the main road but are better displayed in a deep old quarry (44187591) on the south side of the road 220 yards west of the previous locality and consist of well-bedded flags of calcareous siltstone showing small-scale channel-bedding and an abundance of *Chonetes striatellus*, *Camarotoechia nucula* and *Dalmanella lunata* as disarticulated valves mostly convex upwards. Some particularly good specimens of *Serpulites longissimus*, *Michelinoceras* (*Orthoceras*) *imbricatum* (Wahlenberg), *Orbiculoidea rugata* and worm burrows were also found.

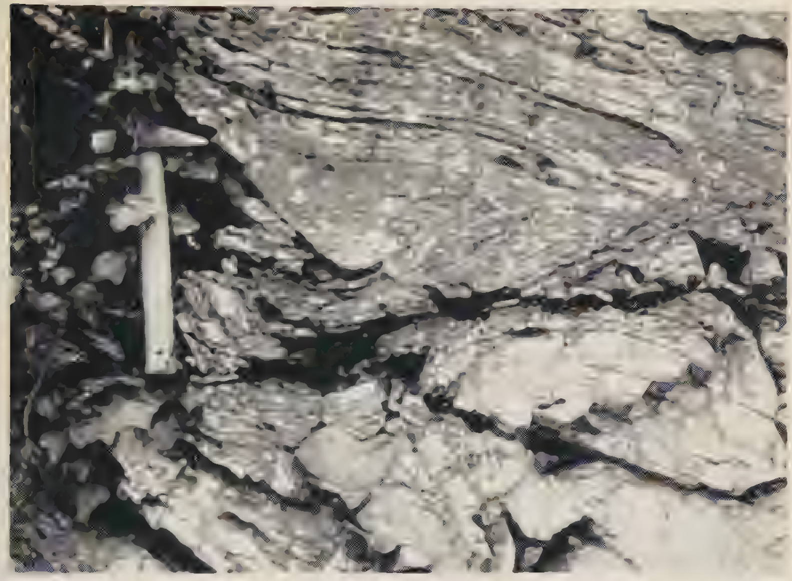
The party rejoined the coach at the top of the hill near Hillpike Farm and drove round the Fiddler's Elbow to the old quarries at Mocktree on the north side of the main road. At the eastern end (41677535) several normal faults were seen, two with fault drag, which displace the easily recognisable junction between the massive Upper Bringewood Beds and the well-bedded lowest Lower Leintwardine Beds. Higher Lower Leintwardine flags rest in a shallow channel upon lower beds of the same division, but seventy yards to the south-west, in a small roadside exposure, these same beds were seen banked up against a cliff of Upper Bringewood massive limestones. The party climbed up to the north face of the quarries and collected *Conchidium knightii*, *Leptaena rhomboidalis*, *Atrypa reticularis*, *Strophonella euglypha*, *Favosites* sp. etc., from the Upper Bringewood limestone and abundant *Dayia navicula*, *Dalmanella orbicularis*, *Sphaerirhynchia wilsoni*, etc., from the calcareous basal Lower Leintwardine Beds.

After scrambling up the quarry face the party walked northwards past Wassell Barn to join the old Ludlow road which they ascended for 160 yards to a small quarry recently worked for 'slates' (41657562). Disturbance of bedding in the surface of the old road was noticed and the branching of an important north–south fault explained. The quarry includes two horizons; at the base, some five feet of very fossiliferous Lower Leintwardine greenish siltstones with *Dayia navicula*, *Lingula lata*, etc., concentrated into parallel depressions on the bedding planes which are aligned east-north-east to west-north-west along the trend of the Todding Channel. On these beds, with slight angular unconformity, rest Upper Leintwardine Beds, the bottom two or three inches of which consist of iron-stained irregularly bedded siltstones full of small pebbles and derived fossils (worn *Orthoceras* sp. with attached *Spirorbis*, *Bel-*

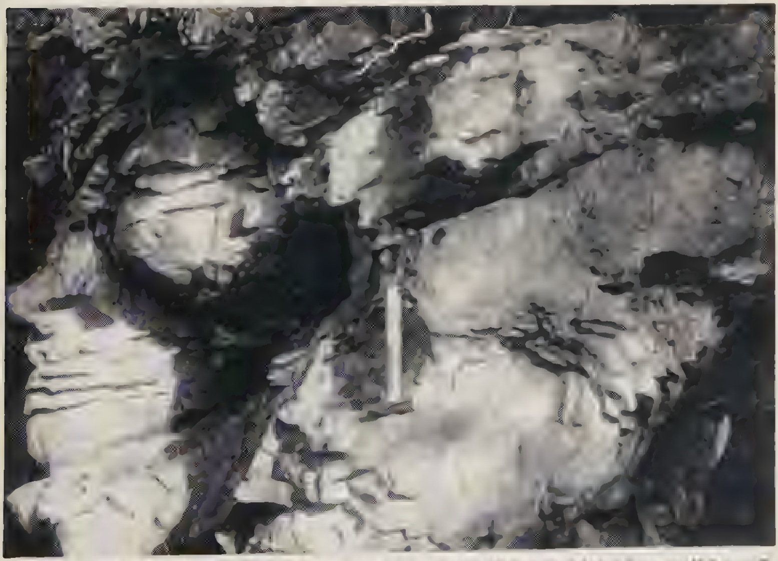
lerophon sp., *Conchidium knightii*) and a characteristic indigenous fauna of *Chonetoidea grayi*, *Beyrichia lauensis* and *Calymene neointermedia*. The topmost six feet consist of barren siltstones of Upper Leintwardine or Lower Whitcliffe type.

Descending the old road to Martin's Shell (41097541) Lower Leintwardine flags were seen on the north side of the track with a layer of derived Upper Bringewood Bed limestone boulders containing *Conchidium knightii*. Some of the flatter boulders show imbricate structure and their position in the Todding channel was discussed. The base of this channel was demonstrated ninety yards further down the track on its north side (41027533) where the Lower Leintwardine flags which fill the channel rest with angular discordance on the lowest Lower Bringewood Beds. The lithology (grey flaggy siltstones with nodular argillaceous limestones) and fauna (*Monograptus tumescens*, *M. chimaera* (Barrande), etc.) of these latter beds were studied seventy yards down the track on the south side (40947530). Before rejoining the coach at the main road below the Cottagers' Comfort Inn, the Director explained how the topographical features above Marlow Farm and Stormer Hall expressed the strike faulting of the beds.

After lunch in Leintwardine the coach was taken to Trippleton Farm half mile south-east of the village, where in the old sunken Trippleton Lane (41207358) glacial drift of local origin occupies a fault hollow and rests on weathered and frost-heaved Middle Elton Beds. Ascending the lane for 200 yards, both banks were seen to expose typical Middle Elton Beds, which are soft olive-green mudstones with closely spaced joints and a conchoidal fracture and the party collected many graptolites including *Monograptus nilssoni* (Barrande) and *M. scanicus* (Tullberg) and dwarfed forms of *Slava* (*Cardiola*) *interrupta* (Broderip) and *Orthoceras* sp. Fifty yards from the top of the lane on the western side the Director demonstrated a striking angular unconformity, higher Lower Leintwardine Beds of the Church Hill channel resting with overlap and marked discordance of dip upon Middle Elton Beds. Forty yards north-north-east of this contact, above the eastern side of the lane, a small crag was examined in slumped Lower Leintwardine siltstones (41167376) and after crossing a fence the party descended to a small quarry on Church Hill (41067373), 140 yards south-east of the T-junction where the road from Leintwardine joins the Whitton–Nacklestone road. Well-bedded minutely laminated hard greyish flags of the higher Lower Leintwardine Beds were examined and abundant *Monograptus leintwardinensis*, *Camarotoechia nucula* and *Sphaerirhynchia wilsoni* were obtained. Several horizons of large derived Upper Bringewood limestone blocks gave further evidence for conditions during the infilling of this—the Church Hill—channel. The party ascended Church Hill to a recently ploughed field directly above the old workings



A. Slump structures in Upper Elton Beds in riverside exposure below the Downton aqueduct bridge (Grid ref. 42877281)



B. Spheroidal weathering along joints in the sandy siltstones of the Lower Whitcliffe Beds; road-cutting near Downton-on-the-Rock (Grid ref. 42907339)

(*Photos by J. H. McD. Whitaker*)

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(41207376) where the Director found several starfish (*Furcaster leptosoma* (Salter) and *Lapworthura miltoni* (Salter)) and crinoid arms from the highest of the famous but elusive Starfish Beds. A bed characteristic of a slightly lower horizon, crowded with *Atrypa reticularis*, *Leptaena rhomboidalis* and *Chonetoidea grayi* and with *Beyrichia lauensis*, *Dayia navicula*, *Camarotoechia nucula*, *Lingula lata*, *Cypricardinia subplanulata Reed* and *Monograptus leintwardinensis* present, was also found in the most easterly of the old quarries (41197376).

After the coach had been rejoined at Trippleton Farm there was a short halt to look at slumped Lower Leintwardine Beds in a roadside quarry (41427298) 700 yards south-east of the farm. Leaving the coach at the T-junction by Nacklestone Farm and walking 100 yards eastwards along the road to Burrington, the party entered a field on the north side of the road and examined the Wenlock Limestone (42397222). Beds of nodular limestone three inches thick, with shale partings, dip at 32° to the north and form a very subdued feature. Some ostracods, small brachiopods and corals were found. From the top of the feature the Director pointed out the straightforward succession of the southern limb of the Downton syncline, from Wenlock Shale by the River Teme to Lower Whitcliffe Beds on the summit of Tatteridge Hill. Since the Excursion, however, a new pipe for the Birmingham Aqueduct has been laid and the supposed fault proved non-existent. The ending of the features must be due, therefore, to the downcutting of the southern margin of the large Tatteridge channel. The glacial history of Lake Wigmore and its northern overflow which cut the Downton Gorge was also briefly explained and the coach was then taken to the Gorge.

Disembarking just north of the Birmingham Aqueduct (42757291) the party descended a small stream bed to the River Teme, seventy-five yards south of the Aqueduct bridge (42877281) where a short search for dendroid graptolites in hard grey Upper Elton flags was unsuccessful. Moving northwards along the west bank of the river a fine slump structure in these beds was noted (Plate 8, A) before passing under the Aqueduct bridge and climbing up through dense nettles to the main track. This was followed past the old quarry faces in Upper Bringewood Beds (well-jointed limestone with a typical fauna) to Bow Bridge where in a small overgrown quarry (43047314) the abundant *Dayia navicula-Dalmanella orbicularis* fauna of the basal Lower Leintwardine Beds was studied. Returning along the main track, the Lower Bringewood Beds were examined briefly (42847299) and several Strophomenids and *Dalmanites* were obtained from the hard grey calcareous siltstones. The coach was rejoined and 180 yards east of the sharp bend in the road at Downton-on-the-Rock it was stopped in a narrow cutting (42907339) where, without getting out, the party noted the typical irregularly bedded yellowish sandy siltstones of the

Lower Whitcliffe Beds, here showing large spheroidal joints (Plate 8, B). The return route was past Downton Castle and through Bromfield to Ludlow.

Wednesday, 6 August

Director: R. Allender

Bishop's Castle area (Ordnance Survey one-inch maps 128 and 129; 1/25,000 maps SO/28, SO/29, SO/38 and a small part of SO/39). The district studied comprises some forty square miles of Ludlovian and Lower Downtonian rocks. This area lies immediately east of the Clun Forest areas studied by Dr. J. R. Earp (1938 and 1940). No previous written accounts exist and the only published map is the 1-inch Geological Survey Sheet 60 S.E. (Mont.), issued in 1850.

About 6000 feet of Ludlovian rocks are seen, of which the upper 5000 feet are broadly similar to those described by Earp in Clun Forest and by Dr. C. H. Holland (1959) at Knighton. In the lower 1000 feet significant facies changes occur. The oldest rocks of the Ludlovian sequence, the Lower Ludlow Graptolitic Shales, can be divided into three facies, eastern, central and western, showing a marked decrease in the number and variety of the shelly fossils from east to west. Changes also occur in the graptolite faunas, the eastern and western facies yielding a *Monograptus nilssoni-M. scanicus* Zone fauna and the central facies a *M. vulgaris* Zone fauna. The beds immediately above the graptolitic shales contain, in places, limestone bands with *Conchidium knightii* and other 'Aymestry Limestone' fossils. These beds are, however, older than the shelf facies 'Aymestry Limestone, being correlated with the lower part of the *Monograptus tumescens* Zone of the Ludlow area (i.e. the Upper Elton Beds).

Structurally, the district comprises two major synclines, one in the east and the other in the west, separated by a highly compressed anticlinal structure. The eastern syncline, between Mainstone and Lydbury North, is cut by three major faults. The central anticlinal disturbance (the southern extension of which is seen at Knighton) is here bounded on the east and west by major faults, and decreases in intensity of compression to the north.

The party travelled from Ludlow to Craven Arms (A49) and here turned north-west along A489 towards the Longmynd. The first stop was at a roadside quarry near Hillend Farm (391873) in *Pentamerus oblongus* beds of Upper Llandovery age, the zone fossil being abundant. Some members of the party climbed the hillside to the north to examine the Llandovery grits resting unconformably on the Longmyndian.

Basal Wenlockian beds were examined next, at a roadside cutting near Plowden (379877), and here *Monograptus priodon* (Bronn) and *Dalmanites* *vulgaris* were obtained. Previously, specimens of *Cyrtograptus lundgreni* (Tullberg) were collected here, so that the 'basal' Wenlockian here corresponds to the higher Wenlockian of other areas, the lower zones being absent.

From Plowden, a traverse was made of the three facies of the Lower Ludlow Graptolitic Shales of the Ludlovian. This began at Totterton, in the eastern facies, where the succession is essentially similar to that of the Ludlow area. The local representative of the Wenlock Limestone (a thin series of calcareous mudstones lying above shales with *Cyrtograptus lundgreni*) was examined in a roadside cutting (366876). Many typical shelly fossils, such as *Dalmanites vulgaris*, *Meristina obtusa* (J. Sowerby) *Strophonella funiculata* (McCoy), *Gypidula* sp. and compound corals, were obtained.

Ascending the succession a lane cutting north-west of Totterton Hall (360877) yielded numerous small brachiopods (including *Dicoelosia* [*Bilobites*] *biloba* (Linnaeus), *Chonetoidea grayi*, *Skenidioides lewisi* (Davidson) and *Leptelloidea segmentum* (Angelin) and trilobites. The fauna and lithology of these beds corresponds extremely closely to the Lower Elton Beds (the 'Barren Beds' of Alexander (1936, 104)) of the Ludlow area. A small quarry in a field 100 yards south-west of this exposure (and stratigraphically just above it) showed shales with *Monograptus nilssoni* and abundant *colonus*-type graptolites. These are similar to the Middle Elton Beds ('*nilssoni-scanicus* Shales') of the Ludlow area.

From Totterton, the party travelled to Bishop's Castle, and thence via B4385 to Upper Broughton. Here the central facies of the Lower Ludlow Graptolitic Shales was seen, in a stream section (303909) 200 yards north of the hamlet. Several members of the party collected specimens of *Rhaphiophorus*, an *Ampyx*-like trilobite especially characteristic of this central facies. *Monograptus dubius*-group graptolites (including *Monograptus vulgaris*) were found fairly commonly, but neither *Monograptus nilssoni* or *M. colonus*-type forms occurred.

After lunch at the Bluebell Inn, Church Stoke, the western facies of the Lower Ludlow Graptolitic Shales was examined in an almost continuous section in Cwm Hopton Dingle (the highest point reached was at 23009046). The lower part of the section exposes dark grey shales with abundant *Monograptus nilssoni*, *M. colonus* and *M. scanicus*, as in the eastern facies, but shelly fossils are almost absent. Above these are shales and siltstones with abundant *M. chimaera*, correlated with the Upper Elton Beds ('*tumescens* Flags') of the Ludlow area. Three slump structures, with eroded tops well shown, were examined in these shales. The shale sequence ends with an intra-formational conglomerate exposed in the east bank of the stream. This is about three feet thick and has local limestone blocks set in a shelly and phosphatised matrix. Above the conglomerate, limestones with abundant shelly fossils (*Chonetes minimus* (J. de C. Sowerby), *Dayia navicula*, *Strophonella euglypha*, etc.) and solid graptolites occur.

From Cwm Hopton, the party travelled back eastwards to Pullets (26559137) and from there walked to a large quarry in Bank Wood (26409093). Here limestone bands with *Conchidium knightii*, *Strophonella euglypha*, *Ptilodictya lanceolata* (Goldfuss) etc., are well exposed, and *Monograptus chimaera* is abundant. These beds are at the same level as the shales with *M. chimaera* in Cwm Hopton Dingle.

From Pullets, a route was taken southwards to Mainstone and thence to the farm at Reilth. The party then walked up the lane south of this farm to a complete section (27618670) through the basal Downtonian *Platyschisma helicites* beds. *P. helicites*, *Modiolopsis*, *Holopella* and *Lingula* were collected, and a thin lenticle yielding *Thelodus* denticles was noted. Elsewhere in the area thick bone-beds occur at this horizon.

The final stop was made at the large quarry at Cefn Einion (28618597) where massive calcareous siltstones, equivalent to the Upper Whitcliffe Beds of Ludlow, were examined. The typical fauna of *Chonetes striatellus*, *Dalmanella lunata*, *Serpulites longissimus* and *Michelinoceras bullatum* (J. de C. Sowerby) was collected.

The journey back to Ludlow was made via Bryn, Lydbury North and Craven Arms.

Thursday, 7 August (first half)

Director: J. D. Lawson

Aymestrey area (Ordnance Survey one-inch map 129, 1/25,000 map SO/46). Aymestrey is the type locality for the limestone of the same name, although Murchison omitted the second 'e', calling the formation the 'Aymestry Limestone' (Murchison, 1834). The correct spelling of the village name is used in this account but the generally accepted mis-spelling is retained in the name of limestone, out of respect for geological usage. Of much greater interest, however, is the disappearance of the limestone only a quarter of a mile west of the village. Alexander (1936) showed the limestone as disappearing beneath the alluvium of the River Lugg but a recent road section up the eastern flank of Mere Hill leaves no doubt that she mistook the Wenlock Limestone for the Aymestry Limestone. The principal object of this excursion was to compare the shelf development of Ludlovian on Yatton Hill (east of Aymestrey village) with the basin-type succession on Mere Hill only a mile farther west, and to discuss their correlation.

From Ludlow, the coach travelled through Elton and Leinthall Starkes at the foot of the Wenlock Limestone scarp on the southern flank of the Ludlow anticline. The limestone is exposed in Wigmore village and here the route was southwards towards Aymestrey (A4110). The director described the spectacular effect of the important Leinthall Earls–Lugg valley fault which is here a strike fault downthrowing to the north. As a result the dip slope of the Ludlow rocks of Gatley Long Coppice is followed to the south by another Ludlow scarp rising to 1000 feet at Croft Ambrey. This fault complex continues north-eastwards through Tinkers Hill to the far side of the Clee Hills. To the south-west it runs along the Lugg valley for a mile or two and joins the Church Stretton fault belt south of Presteigne.

The first stop was at the Yatton gravel-pit, about half a mile north of Aymestrey (428660). The entrance is just south of the roadside pools and permission was kindly given by the owner, Mr. Yeomans. About forty feet of gravels of varying coarseness are to be seen; excellent large-scale fore-set bedding is displayed in the lower half of the southern face. A smaller section of deltaic bedding about twenty-five feet from the base appeared to have the fore-set bedding truncated below and asymptotic above. Many members of the party agreed that if they had observed such a section in the Longmyndian they might well have considered it to be inverted. The boulders were found to be mainly of upper Silurian rocks (with many characteristic fossils) and Old Red Sandstone (with occasional fish fragments). The coarse gabbro which is quite common is considered to be from the Hanter Hill intrusion near Old Radnor, about twelve miles to the west-south-west. Dwerryhouse & Miller (1930, 116) considered that the Wye Glacier travelled eastwards across the north Herefordshire plain and that a tongue of the ice extended northwards to Aymestrey. From the ice-front englacial streams poured the transported boulders and pebbles into the extensive Lake Wigmore which was impounded in the low-lying triangular area underlain by the Wenlock Shale of the Ludlow anticline. The retreat of the ice-tongue then left the conspicuous arcuate feature, now covered with trees, which crosses the valley just south of the gravel-pit.

The coach then drove 350 yards farther south to the lodge of Yatton Court (42576554) where it was left for the rest of this excursion. The party walked eastwards along the southern side of the fields for 400 yards and then ascended obliquely to the foot of the Forestry Commission plantation on Yatton Hill (43206565). The track ascends firstly in a south-easterly direction and then eastwards and exposes the following succession in the shelf facies of the Ludlovian.

Lower Whitcliffe Beds
Upper Leintwardine Beds
Lower Leintwardine Beds
Upper Bringewood Beds
Lower Bringewood Beds

The dip here is to the south-south-east. The first exposure, in the Lower Bringewood Beds, was badly overgrown with nettles but yielded *Shaleria* sp. nov., *Brachyprion* sp. nov. *Leptostrophia filosa* (J. de C. Sowerby), *Sphaerirhynchia wilsoni* and *Chonetes lepisma* to the better protected members of the party. Farther on the harder and more calcareous Upper Bringewood Beds (or Aymestry Limestone) form ribs across the track, and several *Conchidium knightii* specimens were collected. Exposures in the succeeding Lower Leintwardine Beds are almost continuous and though the strata are predominantly shaly and flaggy siltstones some limestone bands crowded with *Dayia navicula* were found. Also collected were: *Sphaerirhynchia wilsoni*, *Dalmanella orbicularis* and *Lingula lata*—the latter fossil suggesting a faunal link with the *Leintwardinensis* Beds of the basin facies. The fauna collected from the Upper Leintwardine Beds above also suggested a correlation with the basin succession. *Shaleria ornatella*, the dominant brachiopod at this horizon near Ludlow and indeed over all the shelf inliers, is here quite rare. The commonest fossils are *Chonetoidea grayi*, *Beyrichia lauensis*, *Calymene neointermedia* and *Encrinurus* sp., thus supporting the correlation of the Upper Leintwardine Beds with the *Beyrichia lauensis* Beds of the basin. Some members had the energy to ascend a little farther and produced samples of the Lower Whitcliffe Beds containing small *Chonetes striatellus* associated with the persistent *Dayia navicula*, as in the Transition Beds to be seen later at Builth. The importance of this Yatton Hill section is that it demonstrates the position of the 'Aymestry Limestone' (i.e. Upper Bringewood Beds) in a succession which shows some strong faunal affinities with the basin succession.

After lunch at the Crown Inn, the party walked westwards along the road following the south bank of the River Lugg. The highest Lower Bringewood Beds were seen by the roadside (42406545); they contain many limestone nodules but the large compound corals and bands of *Conchidium knightii* have not yet appeared. Turning left through the trees along a muddy track, the type section quarry for the 'Aymestry Limestone' (Upper Bringewood Beds) was reached (42306545). Silty seams with shell fragments are not uncommon but a typical fauna was seen: *Favosites*, *Heliolites*, stromatoporoids and a conspicuous band of *Conchidium knightii*. Above the limestone the Lower Leintwardine Beds are dark and shaly and there is no difficulty in finding the junction as there was near Ludlow in the Wigmore Road quarries where the Lower Leintwardine Beds are more calcareous. The fossiliferous debris here provided good collecting, *Chonetes lepisma*, *Dayia navicula*, large *Camarotoechia nucula*, *Lingula lata* and *Monograptus leintwardinensis* being the commonest fossils.

As the quarry is traversed westwards the junction between the Lower Leintwardine Beds and the 'Aymestry Limestone' (Upper Bringewood Beds) maintains a constant height but the base of the quarry rises and the lithology of the exposed limestone becomes siltier. After 300 yards there are no further quarries and the marked change of slope due to the limestone disappears. Excavations in this area indicate that the Bringewood Beds have passed laterally into calcareous shelly siltstones. These beds were examined in the bank close to the gate where the road divides (41776568). The fossils collected, *Chonetes lepisma*, *Leptostrophia filosa*, *Strophonella funiculata* and *Dalmanites vulgaris*, supported the thesis that these shelly siltstones are the lateral equivalent of part of the Bringewood Beds, and the discovery of *Conchidium knightii* here on a previous occasion strongly suggests a silty facies of the Upper Bringewood Beds.

The party followed the left-hand road which curves across a fault valley, on the other side of which the prevailing dip is to the south-east at angles from 25° to 40°. This road connects with a new Forestry Commission road which zig-zags up the eastern flank of Mere Hill Wood and provides an excellent section from the Wenlock Limestone at river level to the '*Beyrichia lauensis* Beds' near the top of the hill. The most striking feature is the undoubted absence of the 'Aymestry Limestone' and also the Upper Elton Beds; in their position between the Lower Ludlow Graptolitic Shales (cf. Middle Elton Beds) and the *Leintwardinensis* Beds (cf. Lower Leintwardine Beds) there occur only about seventy-five feet of shelly siltstones similar to those at the last mentioned exposure.

Just before the Y junction with this zig-zag road there is a highly fossiliferous exposure (41506580) in the Lower Ludlow Graptolitic Shales and the party found numerous well-preserved specimens. Descending nearly to the River Lugg, a short time was spent collecting compound corals and typical brachiopods from the roadside strike section in the muddy Wenlock Limestone (41406595). A return ascent to the Y-junction was made, past the poorly exposed shelly mudstones of the Lower Elton Beds, back into the graptolitic shales. The first two limbs of the Mere Hill road provide a good section in these beds but at the second, rather broad bend, the shelly siltstones are poorly exposed (41416570). *Chonetes lepisma*, *Chonetoidea grayi*, *Sphaerirhynchia wilsoni*, *Beyrichia* sp. and a Monograptid were found. Of greater interest was the discovery by Mr. P. Sproston of a small but well-preserved starfish—the first ever recorded from this immediate area. After a short straight section the road bends and ascends south-eastwards again and provides excellent exposures of the *Leintwardinensis* Beds of the *Monograptus leintwardinensis* Zone, showing obvious faunal affinities with the Lower Leintwardine Beds seen in the Aymestrey quarries, on Yatton Hill and at Leintwardine. The commoner fossils found were *Chonetes lepisma* (larger variety), *Camarotoechia nucula*, *Dayia navicula*, *Lingula lata* and *Monograptus leintwardinensis*. The '*Beyrichia lauensis* Beds' are exposed at the road junction near the top of the ascent but were not examined on this excursion.

The problem of the disappearance of the 'Aymestry Limestone' was briefly discussed. A lateral passage into the 'Lower Shelly Siltstones' of the basin development seemed the most probable solution but the unusual thinness (about seventy-five feet) of these beds, which are several thousand feet thick in Clun Forest, required some explanation. The party then return to the coach waiting near the bridge at Aymestrey.

Thursday, 7 August (second half)

Director: C. H. Holland

Pedwardine inlier (Ordnance Survey one-inch map 129, 1/25,000 map SO/37).

The latter part of the afternoon was spent in a brief examination of the pre-Silurian rocks of the Pedwardine Inlier, described by Cox (1912), who established the following divisions:

Letton Grits and Conglomerates (probably Bala)
unconformity
Dictyonema Shales (Tremadoc)
fault
Brampton Grits and Conglomerates (Longmyndian)

From the road (A4110) south of Walford the inlier could be seen to the west, across a belt of low ground occupied by Wenlock Shale. The Director commented upon the geological setting of the inlier, within the Church Stretton disturbance. The party now motored through Walford to Brampton Bryan (A4113) and then turned southwards along a minor road.

The Brampton Grits and Conglomerates were examined at a roadside exposure (36857186) some 600 yards south of Brampton Bryan. Members discussed the evidence for the Longmyndian age of these conglomerates, with their numerous vein-quartz and some rhyolitic pebbles.

Leaving the coach at the road, the party next proceeded about fifty yards up the track towards Pedwardine Farm. The second exposure, examined by kind permission of the farmer, was in the deeply cut stream course along the northern side of the track. Here (36777080) *Dictyonema* Shales, dipping steeply to the west, are overlain unconformably by the Letton Grits and Conglomerates, which dip gently eastwards. Members obtained many good specimens of *Dictyonema* from the stream bed and inspected the very small exposure of the unconformity and overlying rocks. A few fragments of brachiopod ribbing were obtained from the higher, much-weathered conglomeratic sandstones, but at the request of the Director, very little hammering was done. He commented upon the somewhat slender evidence for the age of the Letton Grits and Conglomerates and said that he had hopes of a future opportunity to examine new exposures of them. Some thirty yards up the stream the Brampton Grits and Conglomerates were again encountered. Their junction with the *Dictyonema* Shales is not exposed, but from the form of its outcrop throughout the inlier Cox had concluded it to be a thrust plane gently inclined to the north-north-west.

The coach was now rejoined at the road and the return made to Ludlow via Leintwardine (A4113).

During the evening there was another showing of coloured slides to illustrate the geology, scenery and architecture of the Welsh Borderland in general.

Friday, 8 August

Director: J. D. Lawson

Builth area (Ordnance Survey one-inch map 141, 1/25,000 maps SO/04, SO/05). Dr. S. H. Straw's paper on the Ludlovian rocks of the Builth area (1937) was the inspiration for the recent intensive studies on these beds by the Ludlow Research Group. The area is thirty miles west-south-west of the Ludlow type region and Straw decided to work out the local faunal succession on its own merits rather than distort it to fit into the 'zones' established by Elles & Slater (1906) at Ludlow. He thus demonstrated the limited application of most of the faunal divisions, including those which he himself instituted for Builth. His distinction between the two major faunas—an outgoing *Dayia navicula* fauna and an incoming *Chonetes striatellus* fauna (Straw, 1937, 411, 412)—has, however, proved of value over most of the Welsh Borderland. Although displaying a thick basin development with extensive slumping, the Builth succession differs markedly from the Clun Forest areas (Kerry, Bishop's Castle and Knighton) in the rarity of hard calcareous siltstones (once known misleadingly as 'grits') in the 'Lower Shelly Siltstones' and in the more abundant shelly fauna showing affinities with the shelf succession. It was presumably much nearer to the edge of the basin.

The major local divisions, with the general basin equivalents, are shown in Fig. 2.

The drive to Builth was via Shobdon, New Radnor and Hundred House (B4362 and A481), but the view was limited by the low rain clouds. The ascent towards Rhiw Rhwystyn to see Graptolitic Shales (07355195) and the slumped basal beds of the *Cyrtoceras* Mudstones (07455185) was omitted for the same reason. The road (B4567) along the eastern side of the River Wye was taken, although it was necessary to turn the bus in the quarries west of the junction so that a right turn could be made into the steep secondary road. The regional dip of the strata is to the south-south-east with a gentle syncline north of Aberedw and a corresponding anticline to the south. Beyond Erwood the structure becomes more complex as the continuation of the Church Stretton fault belt, known here as the Brecon Anticlinal disturbance, crosses the Wye Valley.

At the excellent Llanfaredd road cutting (06755020) in the *Cyrtoceras* Mudstones, good slumped beds and several fossiliferous bands were seen. *Gypidula* sp., *Chonetes lepisma*, *Atrypa rèticularis*, *Dayia navicula*, *Leptaena rhomboidalis*, corals and numerous bryozoa were collected.

The succeeding *Wilsonia* Shales show a marked lithological contrast, consisting of black shales often with silty laminae. The topmost *Pterinea tenuistriata* Beds were seen just before the road turns beneath the railway bridge (07004845); the index fossil was collected and recumbent slump folds observed. In the quarry debris across the railway line near White Hall (07104820) the higher '*Atrypina*' Beds yielded *Sphaerirhynchia wilsoni*, *Camarotoechia nucula*, *Dayia navicula*, *Whitfieldella canalis* (J. de C. Sowerby) and *Pterinea tenuistriata* McCoy. After lunch at the inconspicuous 'Seven Stars' Inn at Aberedw the nearby river section in the *Lingula lata* Beds (08054730) was briefly examined. These topmost strata of the *Wilsonia* Shales represent the widespread *Leintwardinensis* of the *Monograptus leintwardinensis* Zone of the basin facies but no identifiable fossils were discovered.

Continuing the southward traverse along the main road, the coach was parked shortly after crossing the River Edw and the party walked across the railway bridge at Pont Shoni and asked permission at the house before visiting the section in the *Chonetoidea grayi* Beds in the very lowest outcrops in Aberedw Rocks. These terraced crags consist of various divisions of the *Orthonota* Mudstones; the more thickly and irregularly bedded calcareous siltstones show a marked change from the *Wilsonia* Shales below, and a benthonic fauna becomes correspondingly more plentiful. The *Dayia navicula* and *Chonetes striatellus* faunas here overlap and *Shaleria ornatella* is often quite common. *Chonetoidea grayi* is typically abundant though not restricted and the ostracod *Beyrichia lauensis* is both common and restricted. Trilobites also experienced a time of prosperity and the party found *Calymene neointermedia*, *Encrinurus* sp. and *Proetus* sp. in addition to *Chonetoidea grayi*, *Beyrichia lauensis* (small and not common here), *Dayia navicula* and orthoceratids.

There was now a welcome improvement in the weather and even some periods of sunshine which emphasised the beauty of the Wye Valley in this region. The drive continued to Erwood Bridge, where the Wye was crossed and the coach parked whilst the party examined the two higher divisions of the *Orthonota* Mudstones along the Ynys Wye road (Straw, 1937, fig. 2). The Transition Beds, in which *Dayia navicula* is still present associated with the *Chonetes striatellus* fauna, were examined in the quarry opposite Ynys Wye (ask at the house) (08754360). In the succeeding *Chonetes striatellus* Beds the Upper Ludlow fauna reigns supreme and *Dayia* *navicula* is not found; these beds were seen in a small roadside quarry (08204370).

The appearance of the sun encouraged the taking of numerous group photographs at this point, with the beautifully wooded Wye Valley forming an attractive and appropriate background. Further to the west-north-west, just north of this road, there are old quarries (07104405) in the *Holopella* Grits and Shales, the highest division of the Ludlovian at Builth, but there was insufficient time to walk over to them. Instead the party rejoined the coach and were driven back up the valley to Builth Wells itself. Here, faced with a choice of afternoon tea or another exposure, the party elected for the latter and a visit was made to the famous roadside cliff-section in slumped *Pterinea* Beds at Llanddewi'r Cwm (036488) on the Brecon road (B4520). Here the tops of some of the slumps were seen to be eroded and overlain by undisturbed mudstones showing graded bedding on a small scale (see Straw, 1937, 443).

The party then returned in the coach to Ludlow by the same route and the improvement in the weather meant that the topographic expression of the faulting in the Brecon Anticlinal disturbance around Old Radnor and Presteigne could be easily appreciated. The hummocky topography around Shobdon due to the drift deposits from the Wye Valley was pointed out and near Orleton (e.g. Bircher Knoll) the wooded ridge of the end moraine was seen.

For this final evening of the excursion the party collected in the lounge of the Ludlow Arms Hotel and Mr. A. J. Butler proposed a vote of thanks to the directors and secretary of the excursion.

On the Saturday morning a small and ever dwindling residue of the party made an informal architectural tour of Ludlow, with a welcome pause for coffee amidst the Victorian nostalgia of Teff's café.

REFERENCES

Alexander, F. E. S. 1936. The Aymestry Limestone of the Main outcrop. *Quart. J. geol. Soc. Lond.*, **92,** 103–15.

Cox, A. H. 1912. On an Inlier of Longmyndian and Cambrian Rocks at Pedwardine (Herefordshire). *Quart. J. geol. Soc. Lond.*, **68,** 364–73.

Dwerryhouse, A. R. & A. A. Miller. 1930. The Glaciation of Clun Forest, Radnor Forest and some Adjoining Districts. *Quart. J. geol. Soc. Lond.*, **86,** 96–129.

Earp, J. R. 1938. The Highest Silurian Rocks of the Kerry District (Montgomeryshire). *Quart. J. geol. Soc. Lond.*, **94,** 125–57.

———. 1940. The Geology of the South-Western part of the Clun Forest. *Quart. J. geol. Soc. Lond.*, **96,** 1–11.

Elles, G. L. 1900. Zonal Classification of the Wenlock Shales of the Welsh Borderland. *Quart. J. geol. Soc. Lond.*, **56,** 370–413.

——— & I. L. Slater. 1906. The Highest Silurian Rocks of the Ludlow District. *Quart. J. geol. Soc. Lond.*, **62,** 195–222.

Holland, C. H. 1959. The Ludlovian and Downtonian Rocks of the Knighton District, Radnorshire. *Quart. J. geol. Soc. Lond.*, **114,** 449–82.

HOLLAND, C. H., J. D. LAWSON & V. G. WALMSLEY. 1959. A revised Classification of the Ludlovian Succession at Ludlow. *Nature, Lond.*, **184,** 1037–9.

LAWSON, J. D. (and others). 1956. The Ludlovian Rocks of the Welsh Borderland. *Advancement of Science*, **12,** 563–70.

MURCHISON, R. I. 1834. On the Structure and Classification of the Transition Rocks of Shropshire, Herefordshire and parts of Wales. *Proc. geol. Soc. Lond.*, **2,** 13–18.

————. 1839. The Silurian System. London, **1.**

STRAW, S. H. 1937. The Higher Ludlovian Rocks of the Builth District. *Quart. J. geol. Soc. Lond.*, **93,** 406–56.

WOOD, E. M. R. 1900. The Lower Ludlow Formation and its Graptolite Fauna. *Quart. J. geol. Soc. Lond.*, **56,** 415–92.

Field Meeting in the Cambridge District

19–21 September 1958

Report by the Director: C. L. FORBES

Received 29 December 1959

THE OBJECT of the meeting was to demonstrate the currently accessible Jurassic and Cretaceous exposures within reach of Cambridge.

A zonal scheme (in parts tentative) for part of the Upper Jurassic is given below (Table I) to clarify the relationships of the various exposures visited.

The Cretaceous exposures are mostly within the area of Geological Survey N.S. sheets 204, 205, where their relationships may be clearly seen.

Faunal lists in this report are based on specimens, identified by the Director, in the Sedgwick Museum.

Friday, 19 September

The party left the Sedgwick Museum in the afternoon and proceeded by coach to (i) the Great Ouse River Board Pit, Fordham Road, Stretham (516743).[1] This pit was opened in 1952 and was mostly excavated then, but work has since continued sporadically. The brecciated top of the Kimeridge Clay is most likely due to periglacial freeze and thaw conditions; the brecciation is similar to that seen in Gault or Kimeridge Clay below contorted Quaternary gravels elsewhere round Cambridge, but the junction is not here contorted. It is an indication that the Lower Greensand is not *in situ*, but is a solifluxion deposit slipped down from the hill in Stretham village.

The zonal subdivision of the Kimeridge Clay depends on the Director's interpretation of M. R. House's MS. notes made whilst an undergraduate, 1952–4, and should be confirmed by more accurate collecting and identification of its ammonites. The section starts below but does not extend so high as the well-known exposure in the Roslyn Pit, Ely.

The skeleton of *Stretosaurus* [*Pliosaurus*] *macromerus* (Phillips) described by Tarlo (1958, 1959) was collected from Bed 7 of the section (Table II).

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[1] All grid references lie in the 100 km. square 52 (TL).

TABLE I. **Zonal scheme for part of the Jurassic near Cambridge**
(modified by the Director after Arkell and others)

		Zones	Exposures	
			Unconformable Lower Greensand of Roslyn Pit*	
KIMERIDGIAN		*Aulacostephanus pseudomutabilis*	24 ft. at Roslyn Pit,* top not reached	
		Rasenia mutabilis	(*b*) Top beds at Stretham* (*a*) Beds at water-level in Roslyn Pit*	
		Rasenia cymodoce	present at Stretham*	
		Pictonia baylei	(*b*) beds with *Pictonia*, at Stretham* (*a*) beds with *Pachypictonia* at Bury Lane, Sutton† and Sandhills Bridge, Littleport† (R. G. Casey would perhaps put (*a*) and (*b*) in *cymodoce* Zone. Preliminary personal communication, work not completed)	
		Ringsteadia pseudocordata	?Phosphate bed of Bury Lane, Sutton†	
OXFORDIAN	'Corallian'	*Decipia decipiens*	(*c*) *Amoeboceras* (*Priondoceras*) *prionodes* beds of Bury Lane, Sutton† (*b*) *Amoeboceras pseudocaelatum* beds of Fordy Fm, Toll Fm,* Long Stanton Reservoir (*a*) Hancock's Knapwell Ditch fauna (1954)	
		Perisphinctes cautisnigrae	Boxworth Rock	Upware ?Upper part of Coral Rag
		Perisphinctes plicatilis	(*b*) Lower Ampthill Clay of Gamlingay (*a*) Upper Elsworth Rock Series of Elsworth and St. Ives. Corallian of Warboys ?*	Coral Rag* and Coralline* Oolite
		Cardioceras cordatum	Lower Elsworth Rock Series of Elsworth ?missing at Warboys*	Elsworth Rock Series
		Quenstedtoceras mariae	Oxford Clay of Warboys*	proved underground

* Exposures visited by the excursion.

† Unpublished temporary exposure, material in Sedgwick Museum

TABLE II. **Great Ouse River Board's Pit, Fordham Road, Stretham**

		ft.	in.
	11. Argillaceous topsoil	0	9
Lower Greensand (slipped)	10. Fine brown sandy earthy gravel with uneven base, and thinning to south	3–4	
Kimeridge Head	9. Clay breccia, with a well-marked but undulating junction to bed 10 above	4–3	
pseudomutabilis Zone	8. Stiff black clay	0	3
	7. *Ostrea ? delta* Smith in stiff black clay, with common *Aptychus latus* (Parkinson)	0	1
	6. Shaley clay with *Aulacostephanus* sp., etc.	0	9
mutabilis and *cymodoce* Zones	5. Shaley clay with many crushed *Rasenia*, efflorescing white at the exposed face in dry weather, so it may be traced round the pit	0	10
	4. Massive dark blue clay, greenish above and more fissile there, with large crushed *Pictonia* oysters, etc.	3	11
?	3. Pale grey clay, mottled bluish	1	8
baylei Zone	2. Septaria in pale grey clay with *Pictonia* body-chambers uncrushed	0	6
	1. Massive pale grey clay with crushed *Pictonia* becoming hard and very pale at the base. Seen to bottom of pit	4	6
	Total	20	3

(ii) Quarternary, Stretham to Upware. From Stretham the party crossed the bed of the extinct Stretham Mere (indicated by patches of white shell marl in the black peat fields by the roadside), and the rivers Great Ouse and Cam, now running several feet above fen level, to the Upware 'Island'.

(iii) Jurassic of Upware. Here the pits are derelict with the exception of Bridge Pit North, just by the north side of the Fordham road (542722). Neither Gault nor Lower Greensand are present, but the Corallian was well exposed. Members could see the interdigitating lateral passage from Coral Rag to Coralline Oolite, and fossils were collected; chiefly lamellibranchs from the Coral Rag and a few irregular echinoids from the Oolite.

The few ammonites known from the Coralline Oolite all indicate the *plicatilis* Zone, and the exposed Corallian is known to overlie Lower Elsworth Rock Series of the *cordatum* Zone (Arkell, 1937a). The upper limit of age is not clear, ammonites of the *cautisnigrae* Zone being unknown. The next known (Hancock, 1954, 251) fauna, exposed about 1951 in a clay pit (now derelict) at Fordy Farm (542748), one and a half mile north of Bridge Pit North included *Amoeboceras* aff. *pseudocaelatum* Spath and *Decipia* sp., a *decipiens* Zone fauna similar to that described by Arkell (1937b) from Long Stanton and to that mentioned below from Toll Farm, Mepal.

Saturday, 20 September

(i) Barrington. The whole morning was spent at Eastwood's Cement Works, Barrington (396507), last visited by the Association in 1944. The section (Table III) was essentially unaltered since that date. An extensive exposure of Burwell Rock was seen; Cambridge Greensand was well exposed though sparsely fossiliferous in the south-west end of the pit. The extreme south-west end extends into backfilled opencast workings, where the Cambridge Greensand has been worked out. Members collected *Schloenbachia* spp. and other Chalk Marl fossils from frosted blocks on a bench below the Burwell Rock in the north-east part of the pit. Attention was drawn to the unpublished work of Burnaby (1953) on the microfauna of the Chalk Marl.

Chalky Jurassic Boulder Clay, identified by West & Donner (1956) as being of the Lowestoft Advance, was seen at the top of the pit as also was the Holocene valley fill described by Sparks (1952).

The mammaliferous gravel pit near the river (383491) visited by the Association in 1911 and 1944 is now overgrown and full of water in the deeper parts.

TABLE III. **Eastwood's Cement Works, Barrington**

		Boulder Clay and Holocene	variable	
			ft.	in.
Lower Chalk	*Holaster subglobosus* Zone	Very pale greyish white chalk	50 ft. seen	
		(Burwell Rock) Massive gritty chalk	10	0
	Schloenbachia varians Zone ?	Light grey marly chalk	73	0
	Stoliczkaia dispar Zone ?	Glauconitic grey chalk with many phosphate nodules in the lower part, passing up gradually into the chalk above; the lower junction sharply defined and undulating	1	6
Upper Gault		Slightly calcareous grey plastic clay	10 ft. seen	
		Total	144	6

(ii) Cherry Hinton. After returning to Cambridge for lunch the party proceeded first to the British Portland Cement Manufacturers Ltd. pit (484556) between Lime Kiln Close and the Water Co.'s reservoirs at Cherry Hinton. The base of this pit is at approximately the same horizon as the top of the Barrington pit, being thirty feet above the spring issuing from the Burwell Rock across the road from Lime Kiln Close. The section is given in Table IV. The *subglobosus* Zone yielded no fossils, nor were any belemnites found in the Belemnite Marls, but the upper part of the pit yielded abundant *Rhynchonella cuvieri* d'Orbigny and *Inoceramus* spp. including *I. labiatus* (Schlotheim).

TABLE IV. **British Portland Cement Manufacturers, Cherry Hinton**

			ft.	in.
		Topsoil	1	0
Inoceramus labiatus Zone		Rubbly white chalk with abundant fossils	5	0
		Marl, grey	0	3
		Rubbly white chalk	1	2
		Blocky white chalk	4	0
		Marl, yellow	0	6
		Blocky white chalk	4	0
		Pink chalk	0	6
	Melbourn Rock	Nodular white chalk	6	0
Holaster subglobosus Zone	Belemnite Marls	Grey marl		
		Blocky white chalk	1	2
		Grey marl		
		Blocky whitish chalk	20	0
		Soft marly chalk	28	0
		Grey chalk with curvilinear jointing	47 to base of pit	
		Total	118	7

(iii) Underwood Hall. From Cherry Hinton the party went on to the pit at (613570). This is 'No. 2 Westley Waterless' of Penning & Jukes-Browne (1881), called 'Underwood Hall' by Jukes-Browne & Hill (1904, 237–8) who give a section measured by Woods in 1899 and to be found also in White (1932, 37–8) who assigned the whole section to the *Holaster planus* Zone. The pit was found to be a good deal obstructed by nettles, trees and talus, but fossils including a few ammonites were collected.

(iv) Weston Colville. From Underwood Hall the party moved to the pit at the road junction (604535), three-quarter of a mile west of Weston Colville in the upper part of the *planus* Zone (White, 1932, 39, quoting Brighton, 1928) which is still highly fossiliferous. A notable find was a large *Cerithium saundersi* Woods (Sedgwick Museum B81559) preserved inside a *Micraster*.

Sunday, 21 September

(i) Warboys Brick Pit. First visited was the London Brick Company's pit near the railway station, Warboys, Hunts (310818), in the Oxford Clay. The bulk of the exposure is in the *mariae* Zone and has been described by Spath (1939), Arkell's paper (1939) on the Woodham pit being also of use in identifying the Oxford Clay ammonites, of which many were collected by members. In recent years, north-westerly extension of the pit and slipping of the face have greatly improved the exposure of the Corallian at the top, where some ten feet of limestone and silty clay are exposed, the latter yielding large perisphinctid ammonites. If these belong to the *plicatilis* Zone as shown in Table I and as suggested on the excursion, then the underlying *cordatus* Zone must be absent from this exposure.

J. C. Callomon (1960) comments on the poor preservation and puts forward the following solution to the problem: 'There are forms not unlike the Warboys fossils from the Continental *cordatum* Zone (e.g. Aagau); whereas the *mariae–cordatum* Zones saw the maximum of the Boreal faunal transgression, so that the Tethyan Perisphinctids are almost completely absent from these zones in this country, and hence almost unknown. I feel certain that the top beds at Warboys still belong to the *praecordatum* Zone and here yield examples of these missing Perisphinctids. The furthest I would venture with names at present would be: *Perisphinctes* (*Arisphinctes*) spp. *P.* (*?Liosphinctes*) aff. *apolipon* Buckman . . . I think the *praecordatum* Zone ranks as a full zone, for its fauna is quite different from that of the *mariae* Zone. It seems to be as well developed at Warboys as anywhere in the country.'

(ii) Toll Farm, Mepal. Next the party visited the Great Ouse River Board's pit just north-west of the Old Bedford River at Toll Farm, Mepal (435814). This pit was opened about 1955 and exposes some eighteen feet of uniform clay with selenite, the upper part being oxidised to yellow-brown and the lower part uniformly pale grey.

The fauna, listed below, is similar to that described by Arkell (1937b, 64–88), but lacks the *Pomerania* spp. found there. It is interesting to note that the abundant *Amoeboceras* aff. *pseudocaelatum* Spath is a Russian–Arctic species, *A. pseudocaelatum* being based on a type specimen from near Moscow (Spath, 1935).

Ammonites	*Amoeboceras* aff. *pseudocaelatum* Spath. Abundant.
	Amoeboceras spp.
	Amoeboceras (*Prionodoceras*) sp.
	Decipia sp. (one specimen only)
	Perisphinctid nuclei. Common
	Perisphinctes possibly *kirkdalensis* Arkell [ident. W. J. Arkell]
Belemnite	*Belemnites abbreviatus*
Lamellibranchs	*Gryphaea dilatata* J. Sowerby. Common at the SW. end of the pit
	Ostrea delta W. Smith. Rare
	Exogyra nana (J. Sowerby). Sporadic
	Thracia depressa (J. de C. Sowerby)
	Goniomya literata (J. Sowerby)
	Placunopsis radiata (Phillips)
	Chlamys fibrosa (J. Sowerby)
	Cucullaea contracta Phillips?

The whole pit is regarded as lying within the *decipiens* Zone presumably close above the limestone with *Decipia*, which is recorded from ditches nearby by Arkell (1935–48, 354) who also discusses some problem of correlation. The top of the pit is not far below beds with *Amoeboceras* (*Prionodoceras*), which were seen a few years ago in a pit one and a half mile to the south near Sutton village, and perhaps also in a pit one third of a mile to the south-east, though no good ammonites were got from here.

Members found many *A.* aff. *pseudocaelatum* and one large *A.* (*Prionodoceras*) sp. washing out of the clay at water-level, about eighteen feet below the top of the pit.

(iii) Roslyn Pit, Ely. After lunch at the 'Stage Coach' in Market Street, Ely, the party visited the Roslyn (or Roswell) pit of the Great Ouse River Board (551805). Here the Director with an earth auger demonstrated the presence of Lower Greensand, Gault, Cambridge Greensand and Chalk in the glacial erratic described by Bonney (1872). The remnant at present accessible is to be found on the slope down to the water, beyond and below the River Board huts, east of the road leading down to the railway. Lower Greensand *in situ* on Kimeridge Clay was also demonstrated just below the huts, near the road.

The party then moved to the newer part of the workings west of the road where the usual Kimeridge fossils, *Aptychus latus* (Parkinson), *Exogyra nana* (J. Sowerby), *Astarte supracorallina* d'Orbigny and crushed ammonites of various genera were found. An attempt was made to interpret the exposure in terms of the section given by Roberts (1892, 65–9) and the additional information of Arkell (1933, 468). It was evident that *A. supracorallina* ranges well up in the present section, but *Orbiculoidea latissima* (J. Sowerby) was not found at the top.

(iv) Castles Farm. The party split, some going to visit the Cathedral while others went by bus to the Great Ouse River Board's pit (600773) at Castles Farm, North of Soham.

This pit was opened about 1947 and has continued sporadically in work since then. It exposes about twenty feet of dark grey clay with abundant *Inoceramus* and phosphatised ammonites common near the base, which is not far above the Lower Greensand, reputed to have been exposed in a sump.

The fauna listed below was collected when the pit was freshly open.

Ammonites	*Anahoplites praecox* Spath
	— *planus* Mantell var. *inflatus* Spath?
	Hoplites aff. *baylei* Spath
	— aff. *bonarelli* Spath → *rudis* Parona and Bonarelli
	— *dentatiformis* Spath
	— *dentatus* (J. Sowerby)
	— *dentatus* (J. Sowerby) var. *robusta* Spath
	— aff. *dentatus* (J. Sowerby)

	Hoplites latesulcatus Spath
	— cf. *persulcatus* Spath
	— *rudis* Parona and Bonarelli
	— *similis* Spath
Lamellibranchs	*Inoceramus anglicus* Woods
	— *concentricus* Parkinson
	Pecten (*Neithea*) *quinquecostata* J. Sowerby
	Ostrea vesicularis Lamarck
Brachiopod	'*Terebratula*' sp.

It may be deduced that the pit is within the *Hoplites dentatus* Zone; *Anahoplites intermedius* and *Hoplites dentatus-bonarellii* Subzones being both probably present but not yet separated in collecting. The *H. benettianus* Subzone is most likely absent from Cambridgeshire.

The pit has now been abandoned for several years, so that few ammonite fragments were found. Members were however able to collect samples of clay to be examined at leisure for microfossils.

From here the party reunited for tea at the 'Stage Coach', before returning to Cambridge and dispersing.

ACKNOWLEDGMENTS

The Director wishes to express his thanks to the several owners for permitting access to their pits, to Mr. W. E. Doran, O.B.E., Chief Engineer of the Great Ouse River Board, for keeping him in touch with temporary exposures, and for permitting access to the Board's pits, and to Mr. J. D. Hudson for his assistance in the field.

REFERENCES

Arkell, W. J. 1933. *The Jurassic System in Great Britain*. Oxford.

———. 1935–48. A Monograph of the Ammonites of the English Corallian. *Palaeontogr. Soc.* [*Monogr.*].

———. 1937a. The Zonal Position of the Elsworth Rock and its Alleged Equivalent at Upware. *Geol. Mag.*, **74**, 445–58.

———. 1937b. Report on Ammonites collected from Long Stanton, Cambs, and on the age of the Ampthill Clay. *Summ. Progr. geol. Surv., Lond.* for 1935 (2), 64–88.

———. 1939. The Ammonite Succession at the Woodham Brick Co.'s pit, Akeman St. Station, Bucks, and its bearing on the Classification of the Oxford Clay. *Quart. J. geol. Soc. Lond.*, **95**, 135–222.

Bonney, T. G. 1872. Note on the Roslyn Hill Clay Pit. *Geol. Mag.*, **9**, 403–8.

Brighton, A. G. 1928. Notes on the Middle and Upper Chalk of the Cambridge District. *Geol. Mag.*, **65**, 368–71.

Burnaby, T. P. 1953. A Population Survey of Benthonic Faraminifera from the Chalk Marl. *Dissertation for the Ph.D. Degree* [Abstract in Abstr. Diss. Univ. Camb. for 1952–3].

Hancock, J. M. 1954. A New Ampthill Clay Fauna from Knapwell, Cambridgeshire. *Geol. Mag.*, **91**, 249–51.

Jukes-Browne, A. J. & W. Hill. 1904. The Cretaceous Rocks of Britain. 3. The Upper Chalk of England. *Mem. geol. Surv. U.K.*

PENNING, W. H. & A. J. JUKES-BROWNE. 1881. The Geology of the Neighbourhood of Cambridge. Explanation of Old Series 1-inch sheet 51 SW., with part of 51 NW. *Mem. geol. Surv. U.K.*

ROBERTS, T. 1892. *The Jurassic Rocks of the Neighbourhood of Cambridge*. Cambridge.

SPARKS, B. W. 1952. Notes on some Pleistocene Sections at Barrington, Cambridgeshire. *Geol. Mag.*, **89**, 163–74.

SPATH, L. F. 1935. The Upper Jurassic Invertebrate Faunas of Cape Leslie, Milne Land, 1. *Medd. Grønland*, **99** (2).

———. 1939. The Ammonite Zones of the Upper Oxford Clay of Warboys, Huntingdonshire. *Bull. geol. Surv. G.B.*, **1**, 82–98.

TARLO, L. B. 1958. The Scapula of *Pliosaurus macromerus* Phillips. *Palaeontology*, **1**, 193–9.

———. 1959. *Stretosaurus* gen. nov., a giant Pliosaur from the Kimeridge Clay. *Palaeontology*, **2**, 39–55.

WEST, R. G. & J. J. DONNER. 1956. The Glaciations of East Anglia and the East Midlands . . . *Quart. J. geol. Soc. Lond.*, **112**, 69–91.

Field Meeting at Grays Thurrock

19 September 1959

Report by the Director: J. McA. HART

THE OBJECT of this field meeting was to give members a chance to collect from the highly fossiliferous chalk of the Grays Thurrock area and also to visit one of the most interesting flint implement sites on the north bank of the Thames.

The first pit visited was the Wouldham Pit, South Stifford (by kind permission of the manager, D. Bradbury, Esq.), where an eighty foot section of the upper part of the *Micraster coranguinum* Zone is exposed (602785). At the northern end of the pit the Upper Chalk is capped by a considerable thickness of Thanet Sand, itself covered by the Boyn Hill Terrace gravel. Bands of flint were very conspicuous in the chalk and, although mostly nodular, some were observed of a tabular nature which cut across the bedding planes at an angle of up to seventy degrees; minor faulting was also seen, the faults having a general east–west trend and displacing the flint bands by one foot to the south.

The fact that this horizon is in the upper part of the zone was confirmed by the finding of numerous specimens of *Conulus albogalerus* Leske and *Micraster* (*Isomicraster*) *senonensis* Lambert. Other fossils worthy of mention found in this pit were: a tooth of *Lamna appendiculata* Agassiz, *Pecten cretosus* Defrance, *Echinocorys scutatus* Leske, *Serpula ampullacea* J. de C. Sowerby, and *Actinocamax westphalicus* Schlueter.

The party then proceeded to the disused Warren Farm Pit, entering it at the north-eastern corner where the chalk is capped directly by the Boyn Hill Terrace gravel (600794).[1] The chalk here was noticed to be in a very friable state, evidence of this being provided by some recent extensive cliff-falls. It was here that the only recorded specimen of *Inoceramus corrugatus* Woods was found about 1910 by Colonel C. E. Shepherd. Unfortunately there is still only one known specimen. However, there was a local abundance of the coral *Parasmilia centralis* (Mantell), of which several specimens were collected. The discovery of two teeth of *Ptychodus polygyrus* Agassiz in an excellent state of preservation was unexpected. Not many other fossils were found in this pit, however, and after a short period of collecting the party proceeded to the 'Dog and Partridge', North Stifford, for lunch.

After lunch and *en route* for the next locality, while descending Whitehall Lane, Grays, an excellent comparison of the Boyn Hill and Taplow terraces was made, the sudden change in slope on the surface of the road being most noticeable.

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[1] National Grid References lie in the 100 km. square 51 (TQ)

The remainder of the afternoon was spent collecting in Globe Pit, Little Thurrock (by kind permission of Messrs. W. E. Walsham Ltd.) (624784). On entry a path was followed leading to the west side of the quarry, to a spot affording a view of the entire quarry. From here it was possible to see, at the northern end, the Boyn Hill Terrace on a bench level of sixty-seven feet O.D., underlain by about forty feet of Thanet Sand with a very well-defined Bullhead Bed at its base, underlain in turn by the *Micraster coranguinum* chalk; on the eastern face, resting on a bench at forty-nine feet O.D., the Taplow Terrace brickearth and gravel could be seen; while to the south the Flood Plain Terrace and the Recent Alluvium of the River Thames were clearly visible.

Fossils were somewhat scarce in the chalk, but the presence of *Micraster praecursor* Rowe (low *M. coranguinum* Zone form) and *Micraster cortestudinarium* (Goldfuss) indicated a lower horizon of the Zone than anything seen in the morning. Most of the specimens collected here were partly impregnated with limonite and the presence of dendritic manganese was noticeable. Specimens of *Pecten cretosus* Defrance, *Spondylus spinosus* (J. Sowerby), *Micraster coranguinum* (Leske), *Echinocorys scutatus* Leske, *Phymosoma koenigi* (Mantell), *Ventriculites impressus* T. Smith, *Porosphaera glubularis* (Phillips), *Actinocamax westphalicus* (Schlueter), and *Serpula ampullacea* J. de C. Sowerby were collected, and in addition several very large fragments of *Inoceramus* sp. indet. were found, some of which were badly shattered but measured over four feet in diameter.

At one point on the western side of the pit the Bullhead Bed coincides with a layer of flints *in situ* in the chalk, giving rise to the occurrence of flints having the characteristic red and green mottled effect of the Bullhead Bed on their upper surfaces, with their lower surfaces identical with all other flints in the chalk.

The Thanet Sands were seen to consist of fine yellowish-buff sand with traces of silt in the eastern face only. A large sarsen stone about six feet long and four feet wide composed of cemented sandstone was seen at the southern end of the pit; this, I am informed by the quarry owners, was found in the Thanet Sand, and is a remarkably fine specimen. This has since been transferred to the Central Library in Grays.

The Boyn Hill Terrace on its bench at sixty-seven feet O.D. was seen to consist of well-bedded gravel with fairly abundant erratics of ironstone, basalt and vein quartz. This is part of a spread of gravel reaching from Grays to West Tilbury, and in which palaeolithic implements and fossil mammals have been found. Nearby, north of Grays a patch of brickearth of Boyn Hill age is also interesting, because, according to the authors of the Dartford Memoir (Dewey, H. *et al.*, 1924), its formation is '. . . attributed to the Mar Dyke which used to flow southward through the channel now occupied by this brickearth. The uplift of the land relative to sea-level which occurred at the end of the Boyn Hill stage, resulted in the formation of the Grays–Purfleet chalk barrier, behind which the waters of the Mar Dyke were ponded. A channel to the west through the softer Tertiary deposits was subsequently excavated. During this ponding the brickearth was deposited. . . .'

The Taplow Terrace on a bench level of forty-nine feet O.D. consists of brickearth with gravelly partings. These gravels have yielded many specimens of Clactonian implements. Care was taken not to damage the sections as these are all that remain now of a large spread of brickearth which was for many years worked at Grays. This brickearth was once famous for the vast fauna it yielded, including: lion, hyaena, bear, bison, stag, roebuck, elephant, rhinoceros, pig, horse, and beaver, in addition to birds, reptiles, amphibians, fishes, plants and sixty-one species of mollusc (Hinton, 1900).

The Taplow Terrace of Globe Pit is better known today for its abundance of Clactonian implements.

One perfect flint implement is worthy of mention: this is in the possession of the author and was found almost exactly mid-way between the Boyn Hill Terrace and the Taplow Terrace. The method of flaking of this implement indicates a Clactonian age although it was found ten feet above the bench of the Taplow deposit.

The party then adjourned for tea, after which a vote of thanks to the Director was proposed by S. C. A. Holmes, Esq.

REFERENCES

DEWEY, H. *et al.* 1924. Geology of the Country around Dartford. *Mem. geol. Surv. U.K.*

DINES, H. G. *et al.* 1925. Geology of the Country around Romford. *Mem. geol. Surv. U.K.*

HINTON, M. A. C. 1900. Grays Thurrock Area. Part 1. *Essex Nat.*, **11,** 336–70.

———. M. A. C. 1907. Grays Thurrock Area. Part 2. *Essex Nat.*, **15,** 56–88.

WYMER, J. 1957. A Clactonian Flint Industry at Little Thurrock, Grays, Essex. *Proc. Geol. Ass., Lond.*, **68,** 159–78.

Genesis of Sulphide Ores

by DAVID WILLIAMS

Presidential Address delivered 4 March 1960

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ABSTRACT: The hall-mark of specific metals is imprinted on metallogenetic provinces by deep-seated processes in early geological time, the pattern of ore districts being often related to profound crustal lineaments along which ore fluids rise from the depths. Many sulphide deposits are derived from residual hydrothermal solutions emanating from granitic plutons, while granitisation may lead to the concentration of ore-forming metals within resistant country rocks or mobile granitic fluids, and also to their incorporation within hospitable oxide and silicate minerals.

Metamorphism may produce ore deposits, especially in open systems which facilitate the migration of valuable constituents into favourable sites for deposition, and ores may be regenerated by hydrothermal fluids of magmatic, metamorphic or even ground-water type. Among sedimentary sulphide ores those of submarine-hydrothermal origin seem to be dominant.

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1. INTRODUCTION

IN FULFILMENT of the hope expressed at the close of my Address to the Association a year ago I now propose to consider some of the vexed problems of ore genesis, not only for their theoretical interest but also because of their bearing on the future search for minerals. Although our understanding of the origin of certain types of mineral deposits, such as evaporites, chromite segregations, alluvial placers and residual accumulations of bauxite, is tolerable there is a wide variety of ore bodies whose genesis is still shrouded in mystery. For example, despite the vast amount of information gleaned during the past few decades about the copper deposits of Northern Rhodesia, the auriferous conglomerates of the Witwatersrand, the lead–zinc lodes of Broken Hill, N.S.W., and the huge pyritic masses of Huelva, Spain, quite incompatible theories are still propounded to explain their individual modes of formation.

Many current ideas about ore formation were foreshadowed by the prescient concepts of the eighteenth and nineteenth century masters whose contributions have been epitomised in historical reviews by Emmons (1904), Crook (1933) and Adams (1934). During the opening half of the present century widespread homage was paid to the belief, especially championed by Kemp and Lindgren in the United States, that most mineral veins and replacement deposits were generated from hydrothermal solutions of magmatic origin. This popular theory was vigorously challenged by Spurr (1923) who declared that the whole galaxy of metalliferous veins resulted from the forceful injection of highly concentrated ore magmas, and later by Brown (1950) who presented a metallurgical interpretation of ore genesis involving the transport of mineral substances from deep within the earth's crust, not as solutions but as vapours.

Within the past decade or so an increasing number of geologists, dissatisfied with the hydrothermal theory of ore genesis, have resurrected and modernised the idea that in many cases metals were deposited syngenetically within sediments, pyroclastic rocks, lavas and intrusions, often to be concentrated later in fractures, pore spaces or replacement deposits by processes of diffusion, lateral secretion, metamorphic activation or granitisation. It is quite clear that these divergent views cannot be resolved without further detailed field observations, illuminated by the results of intensified laboratory research on the nature and mode of transport of ore fluids, on the mobility of minerals under varying degrees of metamorphism, on isotope fractionation and kindred topics.

2. METALLOGENETIC PROVINCES

In considering certain facets of our present understanding of ore genesis it seems appropriate to start with the concept of metallogenetic provinces, first discussed by De Launay and Urbain (1910), and later elaborated by Spurr (1923) in his stimulating volumes on 'The Ore Magmas'. Within these provinces the rocks and ore deposits, irrespective of their age, may be enriched in a particular suite of elements. In the cogent words of Spurr (1923, **1**, 29) 'the rarer metals are distributed very unequally, and occur mainly in certain provinces. Thus, tin occurs especially in Bolivia, in the Malay Peninsula, and in the Dutch East Indies. It is always closely associated with siliceous igneous rocks, especially granites; but there are vast areas of granite which are not associated with tin. . . . This selection of each metal of certain spots on the earth's crust . . . must mean that there exists in that portion of the earth which is below the crust exposed to our view by erosion, a highly individualised distribution of the metals.' Certainly, if the concept of metallogenetic provinces is valid it seems reasonable to suppose that they are of deep-seated origin since they are not uniquely associated with any particular type of crustal rocks.

Turneaure (1955), in his comprehensive review of metallogenetic provinces and epochs, cites many examples of individual provinces ranging in size from single mining districts, such as that embracing the great molybdenite deposits of Climax, Colorado, to regions several hundred to many thousand square miles in extent. It must suffice here to recall that in Arizona copper mineralisation took place repeatedly between Pre-Cambrian and Tertiary times, that in the plateau country of Colorado, Utah and New Mexico there are many uranium deposits of Triassic, Cretaceous and Tertiary age, and that in the Dutch East Indies there is a thorium province characterised by abnormal amounts of allanite and monazite within Carboniferous and Tertiary granites.

The outermost shell of the earth, extending down to the 'Moho' discontinuity of seismology, is now thought to be about 35 km. thick under the continents and 60 km. under the mountain chains, but descends only some 10 km. below sea-level in oceanic areas. Schematic sections of the continental column depict a discontinuous cloak of sediments draped over a granitic layer, together forming the sial, which is itself underlain by a basaltic layer or sima. In a generalised oceanic column, on the other hand, the crustal rocks beneath a veneer of unconsolidated sediments appear to be of gabbroic composition, corresponding to the 'intermediate' layer of the continents.

Seismological evidence suggests that beneath the sial and sima the upper part of the world-embracing subcrustal mantle is probably composed of ultrabasic material, approximating to peridotite, which by partial melting and extrusion is capable of yielding basaltic and tholeiitic lava flows. Moreover, it is now realised that the upper part of the mantle varies in physical properties from place to place, the variations being doubtless accompanied by compositional and mineralogical heterogeneities within the ultrabasic shell. I suggest, therefore, that metallogenetic provinces are fundamentally due in part to these compositional diversities in the mantle and to the ascent of metal-bearing emanations along crustal flaws which penetrate deeply into the upper part of the ultrabasic mantle. Degassing of the mantle leading to the rise of hyperfusibles such as water, carbon dioxide, chlorine and sulphur, together with silica and alkalies, would provide a means of transporting metals upwards into the crust, where they might eventually become involved in the ceaseless cycle of erosion, sedimentation, orogeny and granitisation.

Wayne Burnham (1959) maintains that in south-western United States and northern Mexico the deposits of a particular metal tend to be concentrated in certain segments of metallogenetic belts whose trends are consistent with major tectonic features. He considers that these phenomena are due to a combination of compositional heterogeneities and associated physical discontinuities established during the same events of early earth history in the deep-seated source regions of the ore. Within the metallogenetic belts described there is a definite and consistent relationship between the distribution of certain metals, notably gold, silver and copper, as economically important constituents of ore deposits, and the distribution of the same or similar metals as trace elements in the sulphide minerals chalcopyrite and sphalerite. His findings are thus analogous to those of Warren & Thompson (1945) who outlined a beltlike tin province in eastern British Columbia that is defined by the presence of tin as a trace element in sphalerite. That each metallogenetic province should be stamped from early geological time with the permanent hall-mark of specific metals seems to bear witness to the operation of deep-seated primordial controls.

3. ABYSMAL SOURCE OF ORES

In many parts of the world the disposition of major ore deposits appears to be related to well-defined lineaments, such as tectonic belts, extensive zones of fracturing, rift valleys and aligned intrusions, which are indicative of profound crustal flaws. Billingsley & Locke (1941) demonstrated that many deposits in the western United States occur where orogenic belts are traversed by later elements such as transcurrent faults, and suggested that heat and fluids, including ore-forming fluids, prefer to rise at or near intersections of major structures where the crust is fractured or weakened to great depth.

The belief that ore fluids may emanate from great depth has recently been fortified by the work of Wisser (1959) in the Cordilleran region of North America, where major structural lineaments and fractures follow the same master trends as the geosynclinal axes, the axes of sharp maximum subsidence in the geosynclines being localised by crustal flaws. He observes that many great mining districts, including Butte, Montana and Leadville, Colorado, are located along pronounced flaws which were activated by diastrophism, in some cases repeatedly since Pre-Cambrian times, so that they tapped the abysmal source of the ore fluids during successive metallogenetic epochs. For example, the Colorado lineament (Fig. 1) is defined by a belt of north-east fractures and dykes, by an alignment of stocks, and by an elongated swarm of ore deposits of Pre-Cambrian to Tertiary age, most productive at Leadville where the lineament intersects the axis of a Permo-Pennsylvanian geosyncline. Originating in the Pre-Cambrian this lineament was reactivated in early and late Tertiary times, metallisation being renewed with each reactivation. The suggestion is strong that consecutive deformations utilised pre-existing fractures and that old fractures in the basement have climbed upward through the cover in response to younger deformations. This idea harmonises well with Schneiderhöhn's concept of regenerated ores, to be discussed in the sequel.

Among the many extensive crustal lineaments which must surely reach great depths are the 1000-mile Rocky Mountain Trench stretching from the Yukon into the United States, and the equally long flaw associated with rocks of Bushveld types extending southwards from the Zambezi along the Great Dyke of Southern Rhodesia, through the heart of the Bushveld Complex itself and beyond the Vredefort Ring into the Orange Free State. Others, more than 100 miles in length, include the Mother Lode in California, the gold-bearing Kirkland Lake and Porcupine fault zones in eastern Canada, and the Owen Rift Fault in western Tasmania passing through the rich mines of Mt. Bischoff and Mt. Lyell. There seems ample justification for supposing that the numerous mineral deposits emplaced within or close to these lengthy lineaments were formed from ore fluids

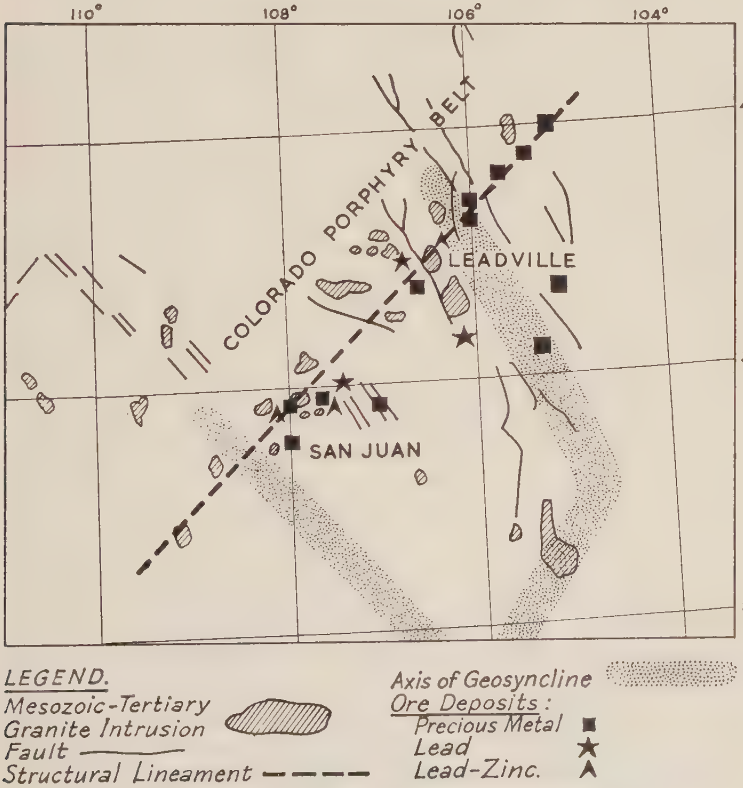

Fig. 1. The Colorado Lineament, U.S.A. (after E. Wisser)

channelled upwards from great depth, though not necessarily from beneath the earth's crust. This is certainly not to aver that the source of most ore fluids lies in the ultrabasic mantle, for once metals have been deposited in the crust they are liable to share the fate of their host rocks in cycles of erosion, sedimentation, granitisation and regeneration within the sial itself. It does seem probable, however, that the loci of plutonic metamorphism, igneous intrusion and mineralisation are often associated with deeply penetrating crustal flaws.

Gregory's contention (1928) that 'the source of the ores appears to lie in a zone deeper than that of the ordinary igneous rocks' gains support from the results of recent research on the isotopic composition of lead ores. It is nowadays assumed that primeval lead which formed when the crust of the earth first consolidated had an isotopic constitution approximating to that of lead in iron meteorites, and that throughout geological time successively younger leads contain higher proportions of radiogenic lead 206, 207 and 208, derived from the decay of uranium and thorium. Accordingly the isotopic make-up of *ordinary* lead is diagnostic for each geological period and is compatible with its 'model age'. On the other hand, *anomalous* leads, derived from the ordinary ones by the addition of radiogenic lead in the crust, are highly irregular in their isotope ratios.

Several investigators, notably Stanton & Russell (1959), have demonstrated that the isotopic constitution of ordinary lead from certain mineral deposits, including Broken Hill, N.S.W., Sullivan, B.C., and Mt. Isa, Queensland, is remarkably uniform and has not suffered any detectable contamination with crustal radiogenic lead. They suggest that these ordinary leads have risen from a deep source, within the earth's upper mantle, and have had but brief contact with crustal material prior to their deposition. Galenas containing ordinary lead are thus thought to have been formed contemporaneously with the rocks that enclose them, either orthomagmatic deposits in mafic rocks derived from beneath the continental crust, or sedimentary deposits associated with seaboard and submarine basalt-andesite eruptions.

It must be admitted, however, as Shaw (1957) has indicated, that essentially uniform leads might also be produced by the mixing, during metamorphism and granitisation, of various leads scattered throughout any heterogeneous sedimentary pile, so that it may not be necessary to invoke a subcrustal source in the mantle. Moreover, Kulp, Amstutz & Eckelmann (1957) have shown that the lead in ore deposits of Tertiary age in the Cerro de Pasco–Casapalca–Morococha district of Peru has almost constant composition, 'suggesting origin from a homogeneous magmatic source derived from an average crustal environment with regard to its U/Pb and Th/Pb ratios'. Nevertheless, the concensus of opinion based on available isotopic data on lead ores from various parts of the world is that ordinary leads are derived from considerable depths within the crust or even from the upper part of the ultrabasic mantle. It is to be hoped that further lead-isotope studies will shed more light on the enigmas of ore genesis and help to determine without equivocation whether certain ore fluids originate within the crust or deeper.

A deep source of ore fluids is also advocated by Hillebrand (1954), who suggests that they 'are not derived from metamorphism of crustal material or through the crystallisation of magmas resulting from palingenesis of crustal material', but probably emanate from a zone of magmation involving the base of the sial and the top of the underlying basaltic sima. He postulates that the ore metals were originally dispersed as segregations in the simatic sub-crust and later ascended to the uppermost parts of the crust along channels created by pre-ore volcanic magmas, the size, number and composition of the ore deposits in any area being partly dependent on the peculiarities of the metallic or sial-metallic segregations tapped during the cycle of magmation. His theory offers a novel explanation of the distribution of metallogenetic provinces and of the spatial, though not parental, relationships between igneous rocks and mineral deposits, and is not incompatible with some of the concepts about the abysmal source of ores already described.

Notable contributions to the study of ore genesis were made by Goodchild (1918, 1919) who tackled the problem from the viewpoint of a metallurgist, visualising that the ore metals were derived by fractionation and concentration from an extensive, deep-seated primordial magma of intermediate-acid composition generated by direct oxidation of an underlying 'metallosphere'. He attached great importance to the action of hydrogen as a mineraliser and attributed the formation of many ore deposits to the injection of liquid matte or metalliferous solutions into tension fractures or other openings in the rocky crust.

A much more ambitious metallurgical interpretation of ore genesis was propounded by Brown (1950) who postulated the gravity separation of immiscible liquid layers during the cooling of an originally molten earth, analogous to that effected in a blast furnace. He envisages a process whereby certain layers of the earth become solid and serve as floors above which immiscible bands accumulate according to their specific gravity. Consequently the top of the peridotite mantle, at a depth of about 60 km., is immediately overlain by a sulphidic ore magma approximately 400 metres thick, composed of a thin basal layer of lead sulphide containing gold and silver, an intermediate horizon of nickel-bearing speiss, and an uppermost thicker layer of zinc–copper matte. Iron source magmas, together with nickel- and platinum-bearing sulphides, are believed to originate mainly near the middle of the basaltic stratum at depths of 40 to 50 km., while the source zone for pegmatitic magmas containing tin and tungsten is thought to lie within the granitic crust at a probable depth of 20 km. (Fig. 2).

Brown asserts that most ores must come from below the base of the granitic layer, probably from just above the mantle, and considers that the common association of ore deposits with igneous rocks, especially granites, is not due to their genetic relationship but to the preparatory heating effect of the intrusives on the earth's outer crust which permitted mineralising fluids to ascend into a zone favourable for ore deposition. Moreover, he contends that the sulphides and metals travel upwards as vapours containing little or no water, motive power being supplied by the weight of solid rock resting on the molten ore magma. According to this hypothesis the distances travelled by various sulphides before deposition is in direct proportion to their volatilities, so that pyrrhotite, sphalerite, galena, chalcopyrite, arsenopyrite, cinnabar, stibnite and realgar are precipitated successively farther and farther away from their source, a supposition which harmonises reasonably well with the known facts of zoning in sulphide ores. Although Brown declares that water plays no vital part in the rise of the ore vapours, he concedes that it may be essential for removing gangue minerals, such as quartz and carbonates, from the host rocks to create space for the deposition of sulphides.

While proclaiming my belief in the deep-seated origin of many mineral deposits I cannot subscribe to Brown's ingenious, though often ingenuous,

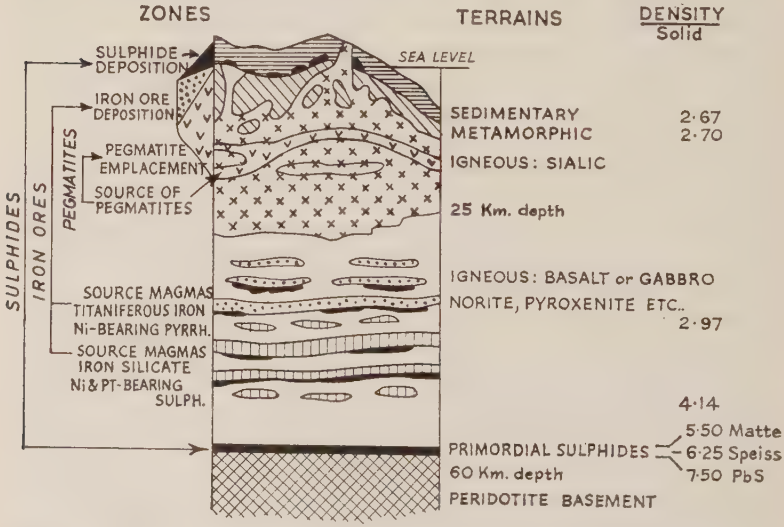

Fig. 2. Generalised constitution of the Earth's crust, according to J. S. Brown's metallurgical hypothesis (after J. S. Brown, with acknowledgments to Geo. Allen & Unwin)

theories on ore magmas, nor can I wholly accept his notions about the simple vapour-transport of sulphides and metals. Indeed, Krauskopf (1957, 1959) has demonstrated that there is little likelihood that volatile sulphides or metal vapours play a significant rôle in ore deposition, though the chlorides of many ore-forming metals are volatile enough to be important constituents of magmatic gas at 600°C.

4. MAGMATIC SULPHIDE ORES

Although metallic oxides do not form immiscible solutions in silicate magmas it has long been known that iron–copper–nickel sulphides are soluble up to 7 per cent in basic magmas and that upon cooling they may separate out as immiscible droplets and, as a result of gravity, accumulate as a separate sulphide liquid. The sulphides normally remain mobile until after the silicates have crystallised and commonly segregate towards the lower margins of the basic igneous bodies where they may constitute valuable copper–nickel ore deposits, as at Sudbury, Ontario and Insizwa, South Africa. Their ore minerals, which are mainly confined to rocks of the norite–gabbro family, consist of pyrrhotite, chalcopyrite and pentlandite, together with platinum, gold, silver and other elements. Crystallisation of the sulphides may induce the concentration of water and other volatile constituents which alter the silicate minerals and may give rise to the formation of hydrothermal sulphide ores.

If the sulphide melt is squeezed it may be squirted towards zones of less pressure, such as sheared or brecciated areas near the margins of the parent basic rock so as to form immiscible liquid sulphide injections, which may grade into more mobile hydrothermal fractions. Such a filter-press mechanism probably accounts for the development of the huge Frood offset deposit at Sudbury and the sulphide veins cutting footwall shales at Insizwa. Despite the voluminous literature on the subject of copper–nickel sulphide ores in basic intrusions (Wilson, 1953; Wager *et al.*, 1957; Wilson & Anderson, 1959) there is still much controversy concerning their precise mode of emplacement. In my opinion their basic magmatic affiliations and intimate genetic relationship to rocks of the norite–gabbro clan brook no denial.

5. GRANITE AND ORE

Modern versions of the prescient ideas on granitisation advocated a century ago by the celebrated French school led by Élie de Beaumont have now gained almost universal acceptance, so that there is a considerable measure of agreement between the 'magmatic pontiffs' on the one hand and the 'migmatic soaks' on the other. Few discordant notes can now be heard in the choir which proclaims with Read (1948) that there are 'granites' and 'granites', some generated from magma and others by the transformation of sialic rocks. For my present purpose the family of granites includes quartz diorite, tonalite, granodiorite, quartz monzonite, granophyre and granite. The frequent close spatial relationship between these rocks and ore deposits has naturally led many geologists to postulate their consanguinity, though others maintain that the association is essentially structural, the rôle of the granite being to prepare channelways for the passage of ore fluids and sites for mineral deposition.

There is little doubt that the base of the sial contains granitic material derived by crystallisation differentiation from the underlying basaltic sima, and that remelting of this granite periodically yields fresh granitic magma. Indeed Read and others have suggested that during crystallisation of the sima copious draughts of residual fluids rich in alkali-silicate ascend to granitise deeply downbuckled geosynclinal sediments within a tectogene. Moreover, these rising fluids probably transport chalcophile and siderophile elements such as iron, sulphur, copper and nickel from their original home in the sima or upper mantle into profound regions of the crust being subjected to granitisation. Once incorporated in the katazone the ore-elements become involved in the subsequent history of the granitic material.

The process of granitisation is usually envisaged as a transformation into granitic rocks of material deposited in a geosynclinal prism. This takes place during orogeny when the geosynclinal sediments and associated rocks, together with the sima, are progressively downbuckled. As a result the sima may be liquefied, its subsequent crystallisation promoting the escape of granitising fluids into the base of the partially or wholly melted sial. Granitising fluids may thus be derived both from the sima and from sediments and other sialic material undergoing metamorphism and anatexis.

Tuttle & Bowen (1958) maintain that 'melting is expected in the earth's crust at depths of 12–21 km. in geosynclinal areas where the initial gradient is on the order of 30°C./km. Complete melting will take place if 9–10 per cent water is available. If the water content is 2 per cent, melting will not take place until some greater depth has been reached.' They contend that this degree of melting would produce a zone in the earth's crust ranging from a few to 20 km. in thickness capable of producing large batholithic masses of granite.

Read (1957) visualises that 'deep in the fold-belt are formed, at an early stage of orogeny, great complexes of granitisation granites associated with migmatites and widespread regional metamorphic rocks. As the orogeny continues, a part of these autochthonous granites becomes partly unstuck from its surroundings and moves higher into the fold structure. This process continues with the movement of true intrusive and magmatic portions late and high, and culminates in the emplacement of the granite plutons, highest and latest, pushing their way as almost solid bodies even into post-orogenic sediments.' Buddington (1959), on the other hand, considers that intrusive plutons may be emplaced at any level in the crust and that granites formed by granitisation are abundant as plutons in the katazone, common but subordinate in the mesozone, and minor or local in plutons of the epizone. Certainly we can all agree that during vigorous orogenic phases the deeply downfolded parts of the sialic crust are intensely metamorphosed and that as a result of anatexis granitic masses become mobile and rise as diapirs to be emplaced at various levels in the thickened crust. In many cases there can be no doubt that the intrusion of magmatic granite was succeeded by the ascent of ore fluids and the formation of mineral deposits.

The recent work of Tuttle & Bowen (1958) amply demonstrates that residual solutions developed during the crystallisation of hydrous granitic magma may display a continuous gradation from hydrous silicate liquid to hydrothermal solution, more especially when the magma contains volatiles such as lithia, carbon dioxide, sulphur, chlorine and fluorine, in addition to water. Moreover, the results of bomb experiments carried out by Morey (1922) and Goranson (1931) clearly imply that during the crystallisation of a granitic melt enormous pressures are developed if the residual solutions are unable to escape.

Bearing these points in mind we may now consider briefly the genesis of the metalliferous lodes of Cornwall, which are unquestionably related to the granites of south-west England. Here, towards the close of Hercynian orogeny mobile potash granites were intruded into folded Devonian and Carboniferous sediments, pinnacles or cupolas of granite, such as those of Dartmoor and Land's End, being probably emplaced at the intersection of ridges produced by Caledonian and later orogenies. Consolidation and slight contraction of the granite hood heralded the intrusion of quartz porphyry ('elvan') dykes, followed in due course by the ascent of tin–tungsten–copper-bearing fluids. These rose rapidly along steeply dipping ENE.–WSW. conjugate faults initiated by gravitational settling and accentuated by the upward pressure of volatiles trapped below the carapace of the molten cupolas. Subsequently, uranium, zinc, lead, silver, antimony and iron were deposited from hydrothermal solutions at successively lower temperatures, mainly in meridional cross-courses which often cut and heave the earlier lodes. This sequence of events culminating in mineralisation is characteristic of many mining fields, granite emplacement being followed by porphyry intrusions and finally by the release of ore-bearing fluids from confinement below the hood of the intrusive granite.

It may be appropriate at this point to discuss the mechanism by means of which the ore fluids concentrate near the granite roof. Gaseous water and bubbles of hydrochloric acid gas, carbon dioxide and hydrogen sulphide rising through the granitic magma act as collectors for volatile halides and metallic sulphides and transport them to the highest parts of the intrusion, especially the cupolas, where they exert their maximum vapour pressure. According to Ringwood's attractive hypothesis (1956) elements possessing halides with high partial pressures, notably tin, tungsten and molybdenum, may be removed from the acid magma by distillation into gas bubbles. The chalcophile elements, including copper, lead and zinc, meanwhile become attached to rising gas bubbles and by a process of natural flotation they concentrate in some favourable locus near the roof of the magma chamber to produce, after partial condensation of the bubbles, an aqueous ore-forming fluid (Fig. 3). During the early, acidic phase of mineralisation tin, tungsten and molybdenum escape from the magma as gaseous halides, to be deposited as cassiterite, wolframite and molybdenite; later, the sulphides are precipitated from aqueous fluids rich in hydrogen sulphide. Fracturing of the granite and overlying roof rocks, due to cooling, facilitates escape of the ore fluids from the magma chamber.

Once certain metals have been introduced into the crust during a metallogenetic epoch they may then take part in the pageant of subsequent

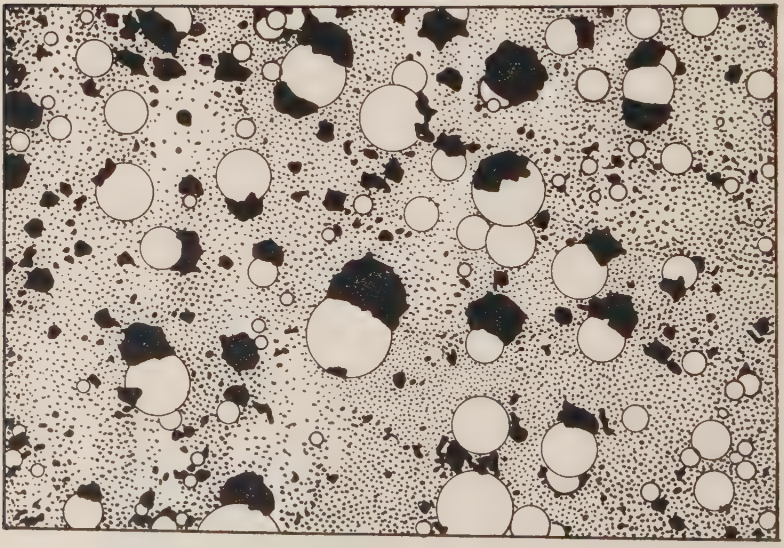

Fig. 3. Glass with gas bubbles and pyrrhotite globules of graded sizes. Granite: Pyrite = 3:1; 75% glass + 25% pyrrhotite; 1410°C: × 25 magnification (after J. Stansfield in 'Assimilation and Petrogenesis-Separation of Ores from Magmas', Urbana, Ill, 1928)

geological events and even be regenerated during a later cycle of metallisation. Thus, tin-bearing lodes and pegmatites formed from residual solutions directly related to intrusive granite plutons may have derived their metal from sediments or volcanic rocks transformed deep within a tectogene into mobile granitic material which then rose to mesozonal or epizonal levels of the crust. Perhaps boron and fluorine acted as agents in collecting and concentrating the dispersed tin content of the mobilised rocks undergoing transformation. During crystallisation of the granitic melt tin would be incorporated partly within the lattices of certain silicate minerals, notably micas, tourmaline and sphene, partly in disseminated grains of cassiterite within the granite, but mainly in cassiterite-bearing lodes and pegmatites formed from volatile-rich residual solutions. Granites in areas embracing stanniferous lodes are thus likely to contain abnormal trace amounts of tin in some of their silicate constituents.

Similarly, in the vicinity of other metalliferous deposits in granitic terrain, such as those of copper, lead and zinc, it is probable that the same metals are also present in abnormal trace quantities in the granite itself within specks of sulphides or the lattices of receptive silicates. Some of the disseminated metals originally scattered through the body of the granite may be leached out by hydrous vapours and concentrated in productive veins. Indeed, I think that some of the base-metal sulphides in pyrometasomatic deposits in limestones alongside transgressive granitic stocks may have originated in this way.

Slawson & Nackowski (1959) have demonstrated that the amount of trace lead in potash felspars within quartz monzonite stocks in the Basin and Range province of Nevada and Utah can be correlated with nearby, related lead ore deposits. They believe that a high trace lead content in the original magma resulted in a corresponding abnormal trace lead concentration in the potash felspars, leaving a residual lead content sufficient to form ore deposits. It is suggested, therefore, that potash felspars in granites from lead-mining districts may contain more trace lead than similar felspars from areas where there is little or no lead production.

In a stimulating and provocative paper on ‘Ore and Granitisation’, Sullivan (1948) contends that throughout geological time the sial has been progressively enriched in ‘volcanic’ rocks, predominantly basic in character, together with associated chalcophile and siderophile elements. He visualises that during granitisation these elements may be segregated into ore deposits, the valuable elements being ‘concentrated in inverse ratio to the extent to which they are incorporated by isomorphous substitution in the common rock-forming minerals’. Thus, tin may accumulate locally in acid granites because its ionic radius is incompatible with entry into the lattices of quartz and felspar, whereas stanniferous deposits are unlikely to occur in rocks containing abundant ferro-magnesian minerals capable of accommodating small amounts of tin within their structures. Similarly, because gold can readily substitute for potassium but not for sodium the precious metal is preferentially concentrated in albite porphyries rather than in orthoclase-rich porphyries. He also contends that the frequent occurrence of auriferous deposits in greenstone areas may be due to the granitisation and mobilisation of gold-bearing basic lavas, the noble metal being driven upwards into veins since it cannot find a home within the chief granite-forming minerals. These propositions are quite acceptable to me.

Sullivan also points out that uranium, thorium, niobium and beryllium, all typical lithophile elements, are chiefly found in old rocks, particularly in association with granites of Pre-Cambrian age, whereas chalcophile metals such as copper, lead and zinc are most abundant in later metallogenetic cycles. Moreover, he is careful to distinguish between synchronous and subsequent granite batholiths, the former being products of granitisation which never reached a magmatic stage whereas the latter attained enough fluidity to move after their formation. Accordingly, synchronous granites exhibit a close spatial relationship to contact metasomatism and ore deposition, the valuable metals unable to enter the lattices of growing granitic minerals being concentrated towards the periphery of the granitisation zone. It seems to me that when the granitic material becomes sufficiently mobile to be intruded at higher levels the metals derived from pre-existing rocks, possibly supplemented by those ascending from subsialic sources, must also rise finally to be expelled with the residual solutions which accumulate during fractional crystallisation of the magmatic granite. Surely many sulphide veins and replacement deposits within or close to intrusive granitic plutons must have been formed in this manner.

Although many of Sullivan's assertions have been challenged, notably by Edwards (1956), I maintain that most of them are substantially valid. Edwards complains that Sullivan's thesis fails to solve the vital problem, namely the mechanism whereby the ore minerals or elements formerly dispersed through a great body of sediments are concentrated and emplaced during granitisation. For my part, I envisage that during this process the less mobile ore-forming metals, including nickel, cobalt and platinum, may be retained and segregated within relict resistant country rocks such as basic volcanics, whereas the more mobile metallic elements tend to travel upwards in a granitising medium, eventually to be incorporated partly in the lattices of hospitable granitic minerals and partly in a residual fluid phase prior to deposition in pegmatites, veins or other types of mineral deposits. Presumably in the case of sulphide mineralisation, sulphur or hydrogen sulphide migrates with the metallic elements derived from the rocks undergoing granitisation. During differential fusion of pre-existing rocks the constituents of low-melting and readily soluble metallic minerals preferentially accumulate in anatectic granite magma rising into the upper parts of the crust.

Sullivan (1957) has recently proposed a tentative classification of metalliferous deposits ostensibly based on field associations, claiming *inter alia* that granitisation has been effective in re-concentrating syngenetic disseminations of base metals from sediments, tuffs and basic lavas, in segregating gold from chloritised carbonated greenstones, and in concentrating copper and nickel sulphides within or close to gabbro-diabase and ultrabasic igneous rocks. Most geologists, however, will be reluctant to accept these bold generalisations while admitting their applicability in certain cases.

He also contends (1959) that the formation of massive sulphide deposits is due mainly to the application of heat to bodies of rock containing dispersed quantities of metals, a process akin to distillation, the separation of sulphide and silicate phases being dependent on relative thermal stabilities and not on their solubility in water. Accordingly, he visualises that the arrangement of sulphides around granitic stocks, like the disposition of metamorphic minerals in the thermal aureole, reflects the temperature stability ranges of the various sulphides and is quite independent of their respective solubilities in water. This is deemed to account for the well-known fact that copper and tungsten usually occur within or in close proximity to granitic stocks, whereas lead and zinc sulphides, with lower levels of thermal stability, are normally driven farther away from the margins of the stocks. Apparently Sullivan attributes the emplacement of the granitic stocks to metasomatism of the host sediments, but he provides no evidence to warrant the assumption that the metals were derived from those sediments, nor any valid reason to disprove the idea that the metals were deposited from magmatic, hydrothermal fluids.

I do not propose to comment now on the interminable controversy concerning the nature of ore fluids save to affirm my belief in the efficacy of hydrothermal solutions (*sensu lato*) as a means of transporting ore constituents to their resting place, though this is far from denigrating the rôle of other collector mechanisms, such as vapours, described by Edwards (1956) and Dunham (1959).

Since the process of granitisation involves the transformation into granitic rocks of sialic material, especially the sediments within a geosynclinal prism, an enormous quantity of combined and connate water, probably cubic miles in volume, must be released during the drastic chemical and physical rearrangements which then take place. Thus, Goodspeed (1952) states that ‘during the granitisation of argillaceous sediments, the transformation of kaolinite to feldspar involves a liberation of 14 per cent of combined water’, the mobilisation and liberation of this water yielding an abundant source of hydrothermal solutions that accompany mineralisation. Apparently these solutions are visualised as a water-front, advancing ahead of the wave of granitisation, dissolving and transporting selected components, including metals, from the heterogeneous sedimentary and volcanic rocks and depositing them under structural control at higher levels in the crust.

Such a process may well give rise to widespread lean mineralisation, to the precipitation of ore minerals in favourable permeable horizons, or in propitious circumstances to the development of mineral veins above the zone of granitisation. In this connection it is pertinent to note that recent experimental investigations in Russia indicate that the solubility of sulphides in aqueous solutions at high temperature is considerably greater than is prevalently admitted. Moreover, heated waters must play an essential rôle in the regeneration of ore deposits, to be discussed in the sequel.

Many Scandinavian geologists, notably Backlund (1952) and Gavelin (1955), insist that there is often an intimate relationship between granitisation and ore formation. Thus, in the Skellefte district of Northern Sweden, where most of the ore deposits consist essentially of compact pyrite accompanied by chalcopyrite, sphalerite and galena, Gavelin considers that the mineralisation is related to granites which originated by palingenesis and granitisation, at least in part of metal-bearing sediments, and that bituminous pelites played an important function in concentrating the metal sulphides.

Bilibin (1950) in an interesting review of the distribution of ore deposits in the orogenic belts of Asia and Europe distinguishes an interior, oceanic zone characterised by vast effusions of basic magma and later alkaline lavas and intrusions, and an exterior, continental zone of potassium granitoids. These two zones are thought to represent former geosynclinal belts created successively within the framework of larger structural units. Igneous rocks of the interior zone are emplaced during the earlier stages of geosynclinal evolution and may be accompanied by the deposition of pyrite and ore bodies containing platinum, chromium, titanium, nickel iron and copper. The acid potassium granitoids of the exterior zones, on the other hand, are intruded during the final stages of orogeny after deep downwarping of the geosyncline, and are typically associated with vein deposits of tin, tungsten, bismuth, molybdenum and later lead–zinc lodes and replacements in limestone. Bearing in mind the possible sedimentary ancestry of cassiterite now found in lodes genetically related to intrusive granite, it is intriguing to note that Bilibin considers terrigenous facies are characteristic of the exterior zones of the metallogenetic belts, for it is in such facies that detrital cassiterite would normally accumulate.

6. METAMORPHISM AND ORE

In considering the rôle of metamorphism in the formation of ore deposits we may adopt Turner's definition (1948) of metamorphism as 'the mineralogical and structural adjustment of solid rocks to physical or chemical conditions that have been imposed at depths below the surface zones of weathering and cementation, and which differ from the conditions under which the rocks in question originated'. These metamorphic changes, effected under the influence of heat and pressure, are not accompanied by wholesale fusion of the original rock constituents but may involve local melting together with the recrystallisation and regroupment of materials by processes of ionic diffusion in the solid state or through the medium of volatiles, especially water. Under such conditions relatively mobile ore constituents, whether initially widely dispersed or highly concentrated, may be mobilised and transported to sites of lower pressure such as fractures, shear zones or the crests of folds.

Schneiderhöhn's (1953, 1954) classes of 'regenerated' and 'secondary hydrothermal' deposits, developed by the reworking or remobilisation of primary ores will be discussed later, for I am immediately concerned with the possible derivation of sulphide deposits by processes of metamorphic differentiation akin to those which yield abundant quartz-rich veins in regionally metamorphosed terrains, quartz–kyanite bodies in high grade pelitic schists, epidosite stringers in amphibolites, and magnetite seams in banded garnet–pyroxene granulites.

Shaw (1954) in a study of the progressive metamorphism of pelitic sediments, from clays, shales and slates to phyllites, schists and gneisses, was able to demonstrate that the amount of nickel decreased slightly during metamorphism, that copper maintained a constant value up to medium-grade metamorphism, followed by a small but clear decrease in the highest, sillimanite grade. Lithium and lead apparently doubled in amount, at trace-element level, but probably as a result of potash metasomatism related to the emplacement of a nearby monzonite. In short, beyond the expulsion of large volumes of water and carbon dioxide the change in composition of the pelitic sediments during regional metamorphism was slight.

An investigation by Taylor (1955) in New Zealand of the regional metamorphism and conversion of greywackes into quartz–albite–biotite schists and of basic igneous rocks into green schists indicated that the chemical redistribution of major and trace elements, including cobalt, chromium, copper and nickel, was so slight in both cases that chemical data could be used to identify the nature of the original rocks, even to the extent of recognising gravitational differentiation in what was originally a basic sill. Similarly, in Sierra Leone, Dunham & Phillips (1958) found that copper minerals in high grade amphibolites could not have migrated more than short distances.

Nevertheless, despite the instances cited above, examples abound of quartz–chalcopyrite veins in amphibolites, seemingly due to metamorphic diffusion, and of copper-bearing quartz–felspar–carbonate veins formed by the migration during stress of material from contiguous country rocks. The extent of migration of various constituents during metamorphism depends *inter alia* on their individual diffusion velocities, on temperature, pressure and concentration gradients, and particularly on the existence of receptive pressure-slacks such as fractures, folds and tensional openings towards which the more mobile elements can diffuse. In an open system of this nature ore constituents may be concentrated into ore deposits, but in a closed or partially closed system the dispersed metallic elements are unlikely to wander far afield and will probably concentrate locally in disseminated oxides or sulphides, or within the lattices of silicate minerals.

De Vore (1955) has calculated that during the transformation of one cubic mile of epidote–amphibolite facies hornblendite into a granulite-facies hornblendite there may be a release of 8 million tons of Cr_2O_3, 4 million tons of NiO and 800,000 tons of CuO. He points out that when copper, nickel and chromium are liberated during the progressive metamorphism of ferromagnesian minerals, specifically hornblende and biotite; when zinc, lead, manganese and titanium are released from these minerals during retrogressive transformations; and when cobalt, chromium, copper, nickel and zinc are freed during the change of biotite to hornblende regardless of metamorphic facies, then under structural conditions favourable to their migration the ore-forming elements may segregate into economic mineral deposits. Analyses of the average trace-element contents of hornblende and biotite from different metamorphic facies clearly imply that their metamorphic transformation is capable of releasing large quantities of material to a dispersed state, materials which in propitious circumstances facilitating mobility could become concentrated into ore deposits. Here then is a possible means whereby metamorphism can create sulphide ore bodies providing there is an appropriate vehicle, such as water and sulphur, for transporting the valuable constituents to a favourable locus of deposition.

It is now well recognised that quartz lenses and veins in metasedimentary and altered igneous rocks commonly result from the infilling of dilation zones and open fractures by silica leached from the wall-rocks, and that this silica may be accompanied by metallic constituents similarly derived. In an interesting account of the gold-quartz deposits of the Yellowknife district of the North-west Territories in Canada, Boyle (1959) demonstrates, with the aid of chemical analyses, that carbon dioxide, water, sulphur, gold and other metallic elements in greenstones were mobilised at high temperature and migrated into cooler regions before being 'literally sucked' into shear zones from points probably up to thousands of feet away and then funnelled towards the surface. Similarly, silica, boron, sulphur and various metallic constituents, mobilised during the metamorphism of sediments, apparently moved through a pervasive medium of gaseous water into dilatant zones in faults, fractures and drag folds. An essential factor in the formation of the mineral deposits was the presence of propitious structural breaks towards which the mobilised ore components could concentrate (Fig. 4).

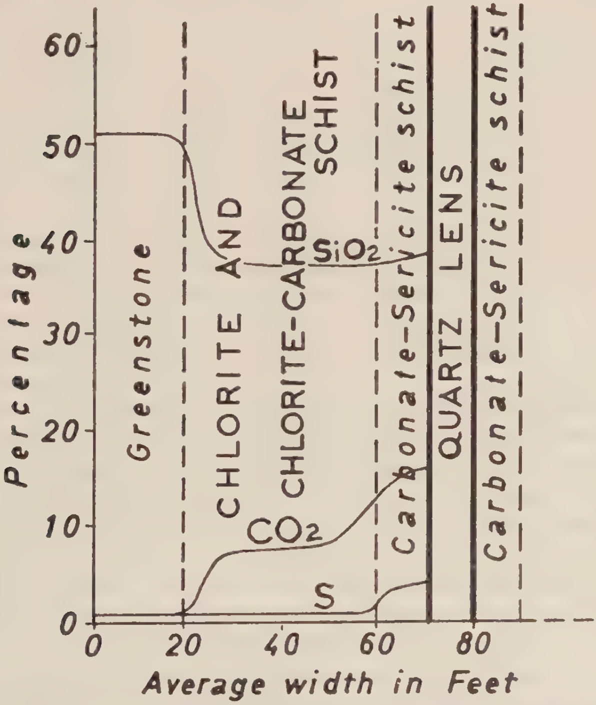

Fig. 4. Chemical changes produced by alteration of greenstone. Composite samples from all shear zones. Yellowknife gold deposits, Canada (after R. W. Boyle, 1959)

The effect of post-ore dyke intrusions on sulphide minerals at Butte, Montana, has been well described by Sales & Meyer (1951). Here, due to thermal metamorphic effects produced by the injection of rhyolite dykes, pyrite-bearing chalcocite ore was converted to massive bornite–chalcopyrite for a distance of several yards from the dyke margins. At the same time enargite was changed to tennantite, and locally pyrite was baked completely to hematite, the changes being due to expulsion of sulphur. The results of this metamorphism can be simulated in the laboratory by heating pyrite and chalcocite together in the absence of excess sulphur, and are simply the outcome of sulphur being driven out of the system. Evidently the heat of the intrusions at Butte was insufficient to promote significant migration of copper, iron and arsenic, these metals being rearranged virtually *in situ* by exsolution in the solid state. Judging from this example it seems unlikely that sulphide minerals travel far when simply heated to the temperature of a rhyolite intrusion, even when they have such comparatively low thermal stabilities as pyrite and chalcocite.

The effect on base-metal sulphides of pressure exerted at moderate temperatures is well exemplified by the behaviour of the beautifully banded sulphide ores at Rammelsberg, Germany, to be discussed in more detail later. Here two ore bodies, each about twelve metres thick and conformably interbedded with Middle Devonian black slates, were subjected to considerable pressure during Variscan (post-Carboniferous) earth-movements so that they now lie on the inverted limb of an anticline. Despite this pressure and an estimated temperature of about 225° C., there was no drastic, wholesale rearrangement or migration of the sulphides, though much of the pyrite suffered cataclasis while a small fraction of the softer sulphides, chalcopyrite, galena and sphalerite, migrated into the thickened crests of drag folds or, less commonly, into small tension cracks in the siliceous hanging walls of the ore bodies. Apparently higher pressures and temperatures than those suffered by the Rammelsberg deposits are needed to produce major migration of sulphide ores, as may have happened to the Pre-Cambrian deposits of Broken Hill, N.S.W., now to be described.

Controversy still rages about the origin of many lead–zinc sulphide deposits in highly metamorphosed Pre-Cambrian rocks, where the ore bodies are conformable with the layering of the contiguous metasediments. Haddon King (1958) has drawn attention to many resemblances between the rock types and ore occurrences at Broken Hill, N.S.W., and those at Franklin-Sterling and Balmat-Edwards in the U.S.A., and Calumet and Montauban-les-Mines in Quebec. All the deposits are in similar lithological environments and have a close association with some particular stratigraphic horizon or sedimentary sequence; all the country rocks have been highly metamorphosed and severely folded under conditions of plasticity; the ores are all high grade, consisting mainly of coarse-grained galena and sphalerite, and their wall-rocks display virtually no signs of alteration; and in none of the five deposits has any genetic relationship between the ore and igneous rocks been proved.

As an alternative to the orthodox concept of a magmatic–hydrothermal origin for these deposits, Haddon King postulates that the ore constituents were originally deposited syngenetically in sediments and that the present characters of the ore bodies are due to successive modification by changing conditions during the long geological history of the respective Pre-Cambrian regions. In particular he visualises the original deposit at Broken Hill as a simple stratigraphically disposed body conformable with the surrounding sediments, and that its ore constituents subsequently migrated to their present sites along fold axes under the influence of intense structural deformation accompanied by successive waves of migmatisation.

Apart from failing to solve the mystery about the original deposition of lead–zinc sulphides in contemporaneous sediments, this attractive hypothesis of intense metamorphic differentiation appears to overcome many of the conundrums that beset proponents of the magmatic–hydrothermal school. On the other hand, Stillwell (1959) reiterates that the Broken Hill lode was formed after regional folding and metamorphism since it clearly alters post-metamorphic dolerite dykes. His authoritative petrological descriptions indicate that successive stages in the formation of the Broken Hill lode involved sericitisation, felspathisation, a high-temperature pneumatolytic phase of replacement by manganese, iron and calcium with the development of manganese-bearing silicates, followed by the deposition from cooler hydrothermal solutions of lead and zinc sulphides together with fluorite and calcite. This theory, which is supported by petrofabric evidence that the ore post-dates deformation and metamorphism (Den Tex, 1958), envisages that the ore fluids rose along major shear zones and then replaced favourable metasedimentary horizons in adjacent anticlines and synclines.

The highly controversial problem of the genesis of conformable sulphide deposits, including those of Broken Hill, has recently been illuminated by lead isotope studies. Apparently *ordinary* leads may represent direct extraction from subcrustal or homogeneous magmatic sources, whereas *anomalous* leads are derived from ordinary ones by the addition of radiogenic lead in the crust. Stanton & Russell (1959) have shown that the isotopic constitutions of ore lead from several conformable lead–zinc deposits, including Broken Hill, Mt. Isa in Queensland and Sullivan, B.C., are invariably ordinary, consistent with its derivation from a rather homogeneous mantle. They suggest that the lead emanated from below the crust to be expelled through the agency of volcanoes and either quickly precipitated as a sulphide on the sea floor or discharged during diagenesis from associated beds of tuff. If this is true it may provide an explanation of the origin of certain syngenetic sulphide deposits, which may later have been subjected to severe metamorphism resulting in migration of the sulphides to receptive structural loci without modification of their lead isotope proportions.

Galena deposited in veins of Thackaringa type, on the outer fringe of the highly metamorphosed area around Broken Hill, contains anomalous lead, prompting Russell & Farquhar (1957) to suggest that the comparatively low-temperature Thackaringa ores were derived from the conformable Broken Hill deposits by a process involving the addition of anomalous proportions of radiogenic leads from the intervening country rocks. They visualise that after the lapse of a few hundred million years part of the lead from the conformable lodes was dissolved and carried upwards through abnormally radioactive rocks to be deposited in simple galena–quartz–siderite veins of Thackaringa type. If this hypothesis is valid one may wonder whether some of the hydrothermal activity at Broken Hill, including the alteration of post-metamorphic dykes, could be ascribed to the period when part of the conformable lead ore was being transferred to higher levels in the crust.

The origin of the Broken Hill lead–zinc sulphide lodes obviously remains *sub judice*, for despite the recent popularity of the idea that they were finally emplaced by the remobilisation and migration of syngenetic sulphides there is strong petrological evidence in favour of their orthodox magmatic–hydrothermal birth. Nevertheless, it certainly seems reasonable to suppose that when deeply buried conformable sulphide deposits of syngenetic or epigenetic origin have been subjected to intense regional metamorphism, as might be expected particularly in many Pre-Cambrian areas, the sulphides may migrate considerable distances by flowing plastically towards low pressure zones, such as fractures and the crests and troughs of folds. It would be strange if there were no such cases.

7. REGENERATED ORES

Within recent years increasing support has been given to the theory, popularised by Schneiderhöhn (1949, 1954), that primary ore deposits may be rejuvenated during tectonic movements to form *secondary hydrothermal* and *regenerated* ores at higher levels.

According to Schneiderhöhn there have been only two primary periods of magmatic and hydrothermal mineralisation since Proterozoic times, namely during the Upper Palaeozoic or Hercynian–Variscan orogeny in Europe and Western Asia, and the Meso-Cenozoic or Laramide orogeny of the Pacific belt in Eastern Asia and Western America. This generalisation is open to question since there are several base-metal sulphide deposits in Europe, including the lead–zinc ore bodies of Stantrg, Yugoslavia, which are almost certainly genetically related to nearby Tertiary igneous rocks. Nevertheless, there are many ore deposits in Europe and North Africa within Triassic, Jurassic, Cretaceous and Tertiary formations which have never suffered an orogeny, but merely epi-orogenic warping together with fracturing related to faults in the Pre-Cambrian basement. These deposits bear no obvious relationship to igneous rocks, but are believed to have been formed from chlorine-rich thermal waters, probably related to Tertiary volcanism, which dissolved metals from deep-seated pre-Triassic ore bodies and carried them upwards into favourable sites in the younger, slightly deformed strata.

Secondary hydrothermal ores, including the lead–zinc deposits of Raibl (Italy), Upper Silesia (Poland) and Bleiberg (Austria), are apparently all of low temperature epithermal or telethermal type characterised by colloform textures. Their minerals include gel–sphalerite, wurtzite, gel–pyrite, marcasite, silver-poor galena, and carbonate gangue. Schneiderhöhn and others confidently believe that these ores were produced by the rejuvenation of Hercynian mineralisation.

Regenerated ores are developed from pre-existing ore deposits in already folded rocks which have suffered still later Alpine-type folding; they include deposits regenerated during orogeny either *with* or *without* contemporaneous intrusions and subsequent volcanism. The old deposits are dissolved and may undergo severe fractionation during transport to higher horizons where they may be deposited as mono-metallic ore bodies consisting almost exclusively of iron-free sphalerite or silver-free galena. According to Schneiderhöhn the complex silver–tin deposits of Bolivia may be regenerated ores.

Strong support for the notion of rejuvenated ores has recently resulted from extensive lead isotope investigations by Cahen *et al.* (1958), who have demonstrated that many of the telethermal lead ores of the Alps and North Africa have 'model' or 'conventional' ages which are older than the host formations, thus implying that they have been derived from more ancient sources. The Raibl and Bleiberg ores appear to have been regenerated without addition of 'primary' or 'juvenile' ore, whereas some of the Moroccan leads seem to be mixtures of migrated and 'juvenile' lead. Moreover, while galenas with model ages comparable to those of the host rocks are rich in silver, their rejuvenated progenitors are impoverished in this precious metal.

Davidson (1960), in a fascinating review of radiogeology and ore genesis, gives the following table of isotopic compositions of lead ores of model ages:

Isotopic Composition of Lead Ores ($Pb^{204} = 1$)

	206/204	207/204	208/204	207/206
Meteoric lead	9.50	10.36	29.49	1.091
Early Proterozoic lead	15.33	15.08	34.61	0.984
Late Proterozoic lead	16.01	15.26	35.39	0.953
Caledonian lead	17.49	15.13	37.18	0.865
Hercynian lead	18.20	15.51	37.97	0.852
Alpine lead	18.71	15.69	38.93	0.833
Lead from sea water	18.93	15.73	38.80	0.836

Thus, according to Davidson, if 'lead of a galena deposit in late Mesozoic strata is found to possess an isotopic composition akin to that of Hercynian lead, it may reasonably be concluded that the galena is a regenerated derivative of an older mineralisation; but if it proves to be of Alpine composition it must be assumed to be derived either from a primary magmatic source or, in the case of disseminated deposits in sediments, as a syngenetic accumulation from sea water'. He also refers to the local regeneration of Hercynian uranium in Portugal, the Erzgebirge and elsewhere in Europe during Tertiary times, and suggests that zones of weakness were reopened and revivified by Alpine earth-movements, thereby facilitating the circulation of solutions in which pitchblende was rejuvenated. In a comprehensive study of the Permian lead–zinc–silver veins in the Freiberg district of Germany, Baumann (1958) clearly recognises the derivation of lead–zinc–copper–iron sulphides by secondary hydrothermal regeneration from a slightly earlier lead–zinc phase of the mineralisation cycle. Finally, reference has already been made to lead isotope investigations which suggest that the galena in Thackaringa type veins near Broken Hill, N.S.W., may have been derived from the much older, conformable lodes of that famous mining field.

Evidence is thus accumulating in favour of the idea that ores may be remobilised and carried elsewhere by rising hydrothermal solutions of magmatic origin or by fluids generated or activated in the crust during tectonic or thermal metamorphism. Andreatta (1954), however, considers that these processes are more liable to dissipate than concentrate the parental ore constituents. In general this criticism seems to be valid, especially in the case of original deposits consisting of widely dispersed metallic constituents, but where surges of chemically active fluids are channelled along reactivated ore-bearing fractures they may well be capable of depositing rejuvenated ores at higher levels in the crust. If this supposition be granted then obviously ores of almost any age, from Pre-Cambrian onwards, may be modified and regenerated to some extent by the effects of later orogenies.

8. THE SOURCE BED CONCEPT

Prompted mainly by dissatisfaction with the epigenetic theory of ore genesis which postulates that metal sulphides were precipitated from fluids of magmatic affiliation, and by a reluctance to believe that sulphide ore bodies may have been deposited simply as syngenetic sedimentary accumulations, Knight (1957) has put forward 'the source bed concept'. According to this hypothesis the sulphide bodies of many mining fields are derived from sulphides that were originally deposited syngenetically at one particular horizon within a sedimentary basin and were later transported in varying degree under the influence of heat. The necessary rise in temperature, it is claimed, might be due to granite intrusion or to deep burial resulting in metamorphism or granitisation.

Knight's concept is based almost entirely on the fact that there is a strict correlation between stratigraphy and ore occurrence in a great many mining districts, including the Northern Rhodesia copper belt, the Kupferschiefer of Germany, the lead–zinc deposits of the Mississippi Valley, Upper Silesia, Morocco and Broken Hill, N.S.W., and the gold-bearing conglomerates of the Witwatersrand, South Africa. Moreover, he suggests that lead–zinc ore bodies are only found in a particular sedimentary environment, especially in limestone or dolomite. Not surprisingly his much too-sweeping and ill-founded contentions have been vigorously assailed, particularly for their cavalier neglect of innumerable sulphide deposits that are almost certainly of epigenetic origin, such as the 'porphyry copper' deposits of North and South America, the lead–zinc pipes and mantos of Mexico, the sulphide veins and replacement flats of the North of England, the copper–nickel ore bodies of Sudbury, Ontario, and the base-metal lodes of Cornwall, Central Wales and the Lake District.

According to Barnes (1959) black shales, which on average contain 20–300 parts per million of copper and 20–400 p.p.m. of lead, are the only sediments with enough metals to be a potential source of constituents to form base-metal ore deposits. He tested the possibility that metamorphism might release metals by lateral secretion from a black shale source by investigating three base-metal deposits, one a contact metamorphic type, one a vein type and one a Mississippi type replacement deposit, alongside each of which there is enough dark shale in the stratigraphic column to be a potential metal source. Chemical analyses indicated clearly that the shale horizons in all three districts were too poor in metals to have yielded by lateral secretion the known tonnages of metals in the ore deposits.

Obviously the source bed concept grossly over-simplifies the enigma of ore genesis by not recognising the existence of undoubted syngenetic, epigenetic and metamorphic deposits, and by its naïve tenet that the stratigraphical control of sulphide ore bodies necessarily implies that the minerals were originally deposited syngenetically in sedimentary basins.

9. HYDROTHERMAL SOLUTIONS

Although discussions concerning the nature of the ore fluid and the mechanisms of ore transport are scattered profusely through the literature of mineral deposits since the days of Élie de Beaumont, in the mid-nineteenth century, these problems still remain unsolved. Because ore minerals are so insoluble in water at any temperature, many theories of non-aqueous ore-forming processes have been postulated, involving transport of the metals as volatile halides (mainly chlorides), volatile sulphides, and even as volatile metals. These mechanisms, however, are now largely discredited. Many writers have advocated that metal sulphides are often carried as colloidal suspensions in aqueous solutions, and latterly increasing support has been given to the notion that ore metals are transported as complex ions, the solubility of the heavy metals being 'changed markedly through relatively small changes in composition of the solutions, thereby providing an additional mechanism for the localisation of sulphides in ore shoots' (Barton, 1959).

Lindgren (1933) was a leading exponent of the belief that major groups of ore deposits were formed by hydrothermal solutions, some of which reached the surface as thermal springs containing traces of metals. The dearth of convincing gradations between hot-spring deposits and workable ore bodies, however, has raised doubts about the popular hydrothermal theory of ore deposition. To some extent this may be due to over-emphasis on the rôle of hydrothermal solutions of magmatic origin, and possibly too small an accent on the activity of metamorphic hydrothermal and ground-water hydrothermal solutions, the latter including both heated meteoric and connate waters.

Reference has already been made to the demonstration by Tuttle & Bowen (1958) that residual solutions developed during the crystallisation of hydrous granitic magma may exhibit a continuous gradation from hydrous silicate liquid to hydrothermal solutions. Such solutions, supplemented by aqueous condensates from a gas phase, seem to be quite adequate vehicles for transporting ore-forming elements from their magmatic source to sites of precipitation. A strong argument in favour of many ore deposits being formed from hydrothermal solutions of magmatic affiliation and not from heated metamorphic or connate waters is that many igneous intrusions are accompanied by adjacent related mineralisation, with its associated hydrothermal wall-rock alteration, whereas other nearby igneous bodies traversing identical wall rocks are devoid of attendant ore bodies.

I need not enumerate the many cogent arguments, convincing enough for me, that have been advanced in support of the magmatic hydrothermal origin of many, probably most, sulphide deposits, save to refer to recent studies by Jensen (1959) on sulphur isotopes and hydrothermal mineral deposits. He states that 'in those deposits that are intimately associated with the intrusive body from which it is believed the ore solutions were derived, the spread in (sulphur isotope) ratio is very narrow, but those deposits that are not associated with an apparent magmatic source exhibit a broad spread in ratio values'. Indeed, he suggests that sulphur isotope ratios may provide a means of discriminating between three different kinds of hydrothermal solutions, namely *magmatic*, *metamorphic* and *ground water* (Fig. 5).

Paragenetic studies indicate that at Butte, Montana, various sulphides were deposited sequentially in three related fracture systems cutting a monzonitic batholith and its attendant quartz porphyry dykes. According to Jensen the relatively consistent values and narrow spread of the S^{32}/S^{34}

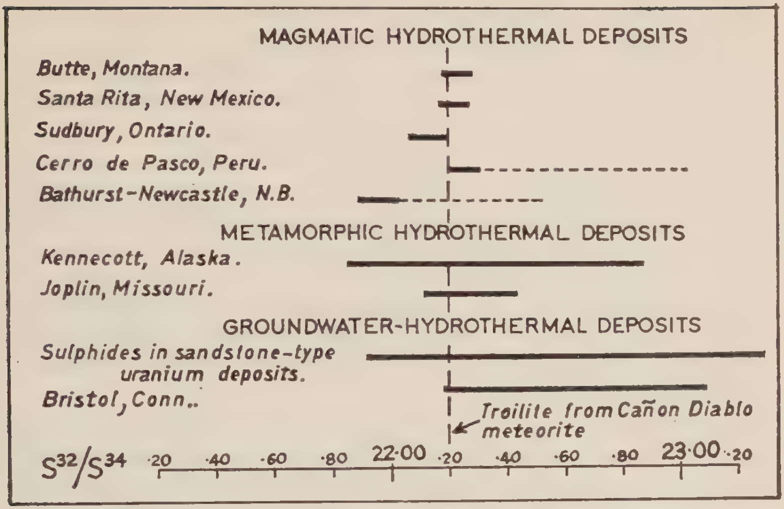

Fig. 5. S^{32}/S^{34} ratios of various sulphide minerals from different mineral deposits (after M. L. Jensen, 1959)

isotopic ratios in sulphur-bearing minerals from the three vein systems confirm previous geological inferences that the sulphides were derived from a common well-homogenised ore solution of magmatic origin. At Sudbury, Ontario, and Cerro de Pasco, Peru, where the sulphide mineralisation also appears to be genetically related to igneous intrusions, the very narrow scatter of S^{32}/S^{34} ratios affords corroborative evidence of a magmatic source for the ore fluids.

'*Metamorphic*' *water* is released by dehydration during the thermal or progressive regional metamorphism of rocks containing hydroxyl-bearing minerals such as kaolinite, micas and amphiboles. Thus, during the transformation of shales with an average of 5 per cent water through slates to schists with 2 per cent water, enormous quantities of metamorphic water are liberated (White, 1957), presumably at high temperature.

Whereas magmatic residual hydrothermal solutions are likely to be homogenised during the final stages of crystallisation of an igneous body, Jensen points out that metamorphic hydrothermal solutions may be derived from heterogeneous sources and have little opportunity of thorough intermingling, so that sulphur-bearing minerals deposited from them might be expected to display a considerable spread in sulphur isotopic ratios. Such chemically active solutions, containing carbon dioxide and other compounds, would probably be capable of mobilising sulphur in the form of hydrogen sulphide and possibly even of transporting sulphides to new sites of deposition. It is tempting to suppose that these waters, released during an orogeny, may remobilise primary ores at depth and carry valuable constituents upwards along fractures to create regenerated ores at higher levels. Indeed, such an origin is suggested by Jensen for the copper sulphide ores of Kennecott, Alaska, which show a very wide spread of S^{32}/S^{34} ratios, and possibly for the famous zinc ores in Palaeozoic limestones at Joplin, Missouri. Recently too, Gray (1958) has boldly, perhaps rashly, postulated that metamorphic waters played an essential rôle in concentrating dispersed metallic constituents to form the copper-cobalt deposits of Northern Rhodesia and the gold ores of the Witwatersrand. The ability of such waters to transport metallic sulphides is still open to question, and quite clearly much more research is needed, including isotopic analyses of ore constituents and fluid inclusions, before definite criteria can be established to discriminate between different kinds of hydrothermal waters.

Ground waters of hydrothermal type include heated circulating surface or meteoric waters, which may penetrate to depths of up to 10,000 feet, and connate waters, originally trapped in ancient sediments and subsequently expressed during their compaction. In regions of volcanic activity both kinds of water may be mixed with thermal waters which may issue as hot springs and are normally characterised by dominant sodium chloride together with a relatively high content of lithium, fluorine, silicon, boron, sulphur, carbon dioxide, arsenic and antimony (White, 1957). Even in hot spring areas such as those of North America, Iceland and New Zealand, isotope studies indicate that the thermal waters are predominantly meteoric and that the contribution from volcanic sources is probably less than 5 per cent of the total volume. Apart from a few quicksilver and antimony deposits no other sulphide ore bodies are known to be definitely related to hot springs or fumaroles (White, 1955).

Since connate waters are highly alkaline and may contain much sulphate and often hydrogen sulphide they may well be capable of dissolving and transporting sulphides, though no positive evidence is yet available to prove that they contribute to the formation of ore deposits. Nevertheless, analysis of various kinds of water in near-surface zones, together with experimental data, proves that many metals, including lead, are appreciably soluble as sulphates and chlorides in surface and underground waters (Konstantinov, 1954). These metals may eventually be precipitated as disseminated sulphides on the sea floor, or in more concentrated form within sandstones containing organic debris, such as the 'Red Beds' copper deposits of the western United States and the U.S.S.R., and some uranium–vanadium deposits on the Colorado Plateau. Their sulphides show a wide range of sulphur isotope ratios, usually with marked enrichment in S^{32}. Such occurrences, due to the concentration of metals by circulating meteoric waters, tend to be small, and erratic in distribution.

Dunham (1952) has suggested that lead veins in the Mendips, possibly of Mesozoic age, might have been produced by the release of 'fossil' hydrothermal fluids trapped in suitable reservoirs during the Permo-Carboniferous metallogenetic epoch. In support of this idea he cites the occurrence of 'waters with up to 2676 p.p.m. barium chloride, which exist in quantity at depths below — 1000 feet O.D. in parts of the Durham Coalfield', apparently representing residual waters from hydrothermal mineralisation. Bearing in mind the appreciable solubilities of metals, even lead, in waters draining mineralised areas, the process visualised by Dunham seems quite feasible, even though its frequency is problematical.

10. EXHALATIVE SEDIMENTARY ORES

Many European geologists, particularly in Germany, have recently advocated a syngenetic submarine-hydrothermal origin for certain concordant sulphide deposits, classed by Schneiderhöhn (1955) as 'submarine exhalative sedimentary ore bodies'. Two excellent examples of this spectacular type of mineralisation are the banded sulphide deposits of Rammelsberg, near Goslar, Germany, admirably described by Kraume (1955), and the pyrite–blende–barite layer of Meggen (Westphalia) equally well recorded in a monograph by Ehrenberg, Pilger and Schröder (1954). In both areas the ore bodies are conformably interbedded in Middle Devonian black slates and have been folded with them during Variscan (post-Carboniferous) earth-movements.

At Rammelsberg the two main deposits, arranged *en echelon* at different stratigraphic levels, are each about 12 metres thick and 500 metres long, and both consist of compact, finely banded ore containing arsenopyrite, pyrite, chalcopyrite, sphalerite, galena and barite. The ore bodies, which lie in the overturned limb of an anticline, are accompanied by 'Banderz' in their footwalls and extremities, comprising alternating bands of slate and sulphides which represent typical transitional formations. It is contended, and in my opinion rightly so, that the ore lenses were formed penecontemporaneously with the contiguous slates and associated volcanic tuffs ejected from submarine vents, and also with the intrusion of magma into a 'swell' or uplift in the region of the present Devonian anticline of the Upper Harz. At the margin between this uplift and the adjacent subsiding Goslar trough which was being continuously filled with muddy sediments, tension fissures opened up permitting magmatic metal-bearing fluids to escape into the sea (Fig. 6).

Arsenopyrite was deposited from the initial limited outpourings, followed by exhalations of silica and, after an interval, by a more prolonged influx of metallic solutions into a depression on the sea floor. The chemical composition of the hydrothermal solutions changed progressively so that at first iron, then copper, zinc, lead and finally barium were the principal metals deposited. After another short interval a second strong inflow of hydrothermal solutions, changing likewise in composition, led to a similar sequence of ore deposition, starting with predominant pyrite and ending with almost pure barite.

Following their solidification and burial beneath later sediments the ore bodies were overturned, the harder pyrite suffering cataclasis while the softer sulphides recrystallised and in part migrated from the limbs to the crests of drag folds or moved in comparatively trivial amounts into nearby tension cracks in the siliceous hanging-walls. Mineralogical studies indicate that the rock temperature during folding was approximately 225° C.

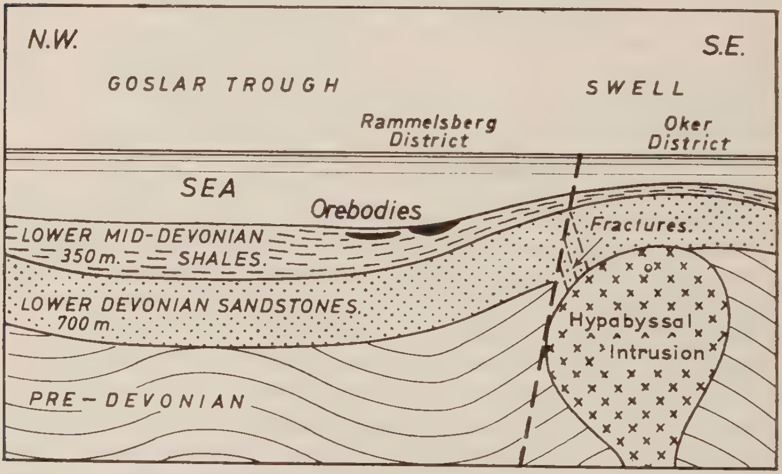

Fig. 6. Schematic diagram illustrating the origin of the Rammelsberg ore bodies, Germany (after E. Kraume, 1955)

I have described the Rammelsberg deposits at some length because they impress me as a type of ore body which is probably more common than is realised, and because they demonstrate the relatively slight mobility of sulphides even when subjected to considerable pressure, involving almost complete tectonic inversion, and fairly high temperature.

Like the Rammelsberg ore bodies, the analogous deposit at Meggen is of syngenetic submarine-hydrothermal origin, the sulphides being precipitated on a muddy sea floor in stagnant waters heavily laden with metallic exhalations issuing from a nearby igneous source. It must be admitted, however, that the chemical reactions entailed in the precipitation of the sulphides are quite imperfectly understood. The banded and colloform textures of the Meggen deposit suggest that it was formed from hot concentrated aqueous metal-sulphide sols which flocculated rapidly in contact with electrolytes in the chilling sea-water, the sulphides settling down as amorphous gels to produce a flat submarine mound-cone about 10 square km. in extent.

Whether the processes advocated to explain the genesis of the Rammelsberg and Meggen deposits can also account satisfactorily for the origin of some other conformable, banded sulphide ore bodies, such as those of Mt. Isa, Queensland, and Sullivan, B.C., is still a matter for conjecture. Certainly in many areas of seaboard and submarine volcanism, especially where tensional fractures are developed along a sinking coastline, large quantities of metalliferous fluids, including sulphates, chlorides and fluorides, may escape into the sea as a prelude to ore deposition.

Oftedahl (1958), adopting 'a volcanologist's approach to ore geology', emphasises that crystallising acid magmas emit copious gases containing a variety of metals, as testified for example by their deposition around fumaroles in the Valley of Ten Thousand Smokes in Alaska, and that acid pyroclastics are not only much more abundant than is generally recognised but are also often genetically associated with ore deposits. From evidence afforded by the pyrometasomatic ore bodies in the Oslo region of Norway he concludes that magmatic gases given off at a late stage in the crystallisation of an acid magma contain iron as the dominant element, then copper, zinc and lead, and in decreasing abundance, bismuth, antimony, arsenic and traces of nickel, cobalt and other metals. He contends that when gas emission takes place under the sea the soluble heavy metal gases disperse rapidly and give rise to sedimentary ores. The insoluble gases either bubble through the water or their metals are at once 'precipitated on the sea floor as a bed of oxide, sulphide, or possibly carbonate in the immediate vicinity of the gas emission'.

According to Oftedahl gas exhalations, related to the ejection of acid pyroclastic tuffs, may be the source of many pyrite and magnetite ore beds in the Caledonides of Norway, of iron ores in Central Sweden, and of limonite beds at Lahn-Dill in Germany. He also suggests, albeit tentatively, that the famous lead-zinc ore bodies in limestones of the Mississippi Valley and Upper Silesia may be assigned to the distant type of exhalative-sedimentary deposit, the metals being originally dispersed extensively over sea basins from far-distant centres of emission. Moreover, he also hints that the bedded copper deposits of Northern Rhodesia–Katanga and Mansfield, Germany, may belong to this class of deposit. But when he misinterprets some old descriptions of the huge pyritic masses of Rio Tinto, Spain, and regards them as chemical precipitates 'of the iron (and sulphur?) of the submarine gas emissions from explosive granitic magma', I have special reasons for mourning that still another geological partisan should weaken his arguments by excessive zeal! (Williams, 1934). Nevertheless, I firmly believe that the exhalative-sedimentary theory is quite capable of satisfactorily explaining the origin of certain concordant sulphide deposits.

11. SEDIMENTARY SULPHIDE ORES

Controversy still rages concerning the origin of many stratigraphically controlled sulphide ore bodies of wide areal extent and very limited thickness. That some are of submarine-hydrothermal derivation, due to volcanic exhalations, seems highly probable, but whether metals derived from the erosion of pre-existing rocks can be concentrated sufficiently in marine environments to form sulphide ore deposits is open to doubt.

The average concentration of most metals is greater in shales than in sandstones, limestones and dolomites, and particularly in black shales where, for example, the mean concentrations of copper, lead and zinc are respectively 20–300, 20–400? and 100–1000 p.p.m. Deposition of metals from sea-water may be effected by the *precipitation of sulphides* within bottom sediments or in isolated basins of reducing conditions, by *adsorption* on hydrated manganese and ferric oxides, clay particles and organic matter, or by *biologic processes*. According to Krauskopf (1956) adsorption provides the most satisfactory means of removing metal ions from sea-water, supplemented by biologic processes for the extraction of vanadium, nickel and probably cobalt and tungsten, local precipitation of sulphides being a contributory but certainly not a major control. Some writers stress the importance of plankton swarms in extorting metal ions from sea-water by adsorption, and others emphasise the precipitating effect of sulphuretted hydrogen produced by the bacterial reduction of soluble sulphates or by the anaerobic bacterial decay of dead organisms. Certainly the formation of mineral deposits by any of these processes requires prior entry into the sea of quite abnormal amounts of metals. If these are not introduced by seaboard or submarine volcanic exhalations then they must be imported by groundwaters and streams draining metal-bearing land masses undergoing weathering and erosion.

Consider first the copper–lead–zinc mineralisation in the Permian Kupferschiefer at Mansfeld in Central Germany, usually regarded as due to syngenetic deposition in shallow marine water of the black shale environment. The ore bed, averaging less than a yard in thickness, is roughly divisible into a basal layer containing disseminated copper sulphides, restricted to areas only a few miles across, overlain by a more extensive galena-rich horizon and an uppermost, still more widespread zinc layer rich in sphalerite. Deans (1950) suggests that the metals may have been conveyed into the Zechstein Sea largely in meteoric groundwaters issuing from the mineralised Rotliegende, and that the accompanying 'traces of vanadium, nickel and molybdenum may be biogene concentrations of humus soils or aquatic organisms'. Some syngeneticists suppose that the likely source of the metals lay in the heavily mineralised mountains of the Harz and Erzgebirge which were exposed to erosion during the arid and semi-arid climate preceding and contemporaneous with ore deposition in the Kupferschiefer, and that some previous concentration of the metals may have taken place in a red-bed environment. It is significant that in the equivalent Marl Slates of northern England, Westoll (*in* Deans, 1950) has discovered head-structures of fossil fishes partly replaced by ore minerals, including galena, sphalerite, chalcopyrite and bornite, in a manner strongly suggesting that their mineralisation was effected before final compaction and lithification of the sediments.

Deans is tempted to infer that the deposition of sulphides in the Kupferschiefer may have been 'an initial minor phase of the established succession of chemical precipitates—carbonates, sulphates, halides—which characterises the Zechstein'. This recalls the suggested paragenetic sequence of deposition of copper–lead–zinc–manganese–iron in littoral and shallow water zones of ancient basins, postulated by Konstantinov (1954) in spite of the expectation that the least soluble metal would be deposited first and the most soluble last. No satisfactory explanation has been offered to account for the solution and transport to the basin of deposition at Mansfeld in a comparatively short time of vast quantities of lead, presumably as the chloride (PbCl), together with more readily soluble copper and zinc. I prefer to envisage with Dunham (1952) that the metals were mainly fed into the Zechstein Sea by thermal springs, probably of igneous affiliation.

Discussion on the genesis of the Northern Rhodesia–Katanga copper deposits continues unabated. In the early 1930s the ore beds were generally thought to have been mineralised by hydrothermal solutions emanating from subjacent now-exposed granites, but when these selfsame granites were proved to be older than the copper-bearing horizons the 'epigenetic school' was ousted from favour by syngeneticists who postulated that the sulphides of copper, cobalt and iron were derived from the weathering of adjacent land surfaces and then deposited in the stagnant bottoms of epeiric seas or lakes (Brummer, 1955). Quite recently, however, a novel epigenetic hypothesis, invoking hydrothermal solutions from an unexposed magmatic source, has been welcomed in certain quarters (Darnley, 1960).

Briefly, the Copperbelt deposits, which are concentrated along an arc of tectonic disturbance about 320 miles long by 40 miles wide, are mainly enclosed concordantly within Roan sediments in the lower part of the 25,000 feet thick, late Pre-Cambrian Katanga System. In Rhodesia the ore horizons are strictly confined to thin argillaceous beds or thicker sandy layers in the dominantly arenaceous Lower Roan sediments, whereas in Katanga Province the stratified copper–cobalt mineralisation is chiefly in dolomites of the Upper Roan, with subordinate amounts of disseminated copper, lead and zinc in limestones near the base of the overlying Kundelungu formation. Significantly, copper, cobalt, zinc and lead also occur in admittedly epigenetic ore bodies within these Kundelungu limestones, including the rich lodes of Kanshanshi and the huge chimney-like massive deposit of Prince Leopold Mine, Kipushi (Fig. 7).

Garlick (1959, and *in* Brummer, 1955), champion of the syngenetic school, visualises the following, much abbreviated, sequence of events. After prolonged arid erosion when widespread mineralisation in the Basement sediments and granites suffered profound leaching, the sea encroached upon the land and with the onset of more humid conditions the water-table rose so that meteoric waters flushed soluble metals towards the sea where they were deposited in stagnant water as biochemical sulphide precipitates. No sulphides were deposited in the oxygenated zone close inshore, but farther out where muds were being laid down in deeper water, bubbling sulphuretted hydrogen generated by the bacterial decay of dead plants and animals caused the precipitation of copper, cobalt and iron sulphides in parallel zones successively more distant from the shore, to form the Lower Roan ore horizons. With further encroachment of the sea rich disseminations of copper and cobalt were subsequently deposited in Katanga among algal reefs and dolomites of the Upper Roan, and still later, streams carried copper together with lead and zinc into Lower Kundelungu seas where limestone was being formed.

Deep burial, folding and metamorphism of the Katanga sediments was accompanied by recrystallisation of the sulphides, which thereby acquired epigenetic traits, while some of the disseminated deposits were mobilised and transported by lateral secretion into major fractures where they rose to produce transgressive epigenetic ore bodies such as those of Kansanshi and Kipushi.

Although this attractive hypothesis accords well with the bedded and widespread extent of the mineralisation its validity is dependent on the assumption that erosion of the Basement rocks was capable of supplying intermittently and during comparatively brief periods of sedimentation enormous tonnages of copper, iron and cobalt. Moreover, it seems unlikely that biologic processes, or adsorption, would be almost equally effective in precipitating sulphides in conditions conducive to the deposition of such diverse kinds of sediments as shales, sandstones, marls, limestones and dolomites. Sulphur isotope studies on the Rhodesian copper deposits by Bateman & Jensen (1956) indicate that the sulphides might have been formed either from hydrothermal epigenetic solutions or syngenetically by the action of hydrogen sulphide of biogenic origin, but not by the bacterial reduction of copper sulphate. Furthermore, unless the sulphides have migrated since their original deposition the presence in Katanga of copper sulphides in calcareous algal reefs suggests that there they were not precipitated under reducing conditions. Finally, the occurrence of related and admittedly epigenetic transgressive ore bodies in the Lower Kundelungu limestones, including the pipe-like copper–cobalt–lead–zinc mass at

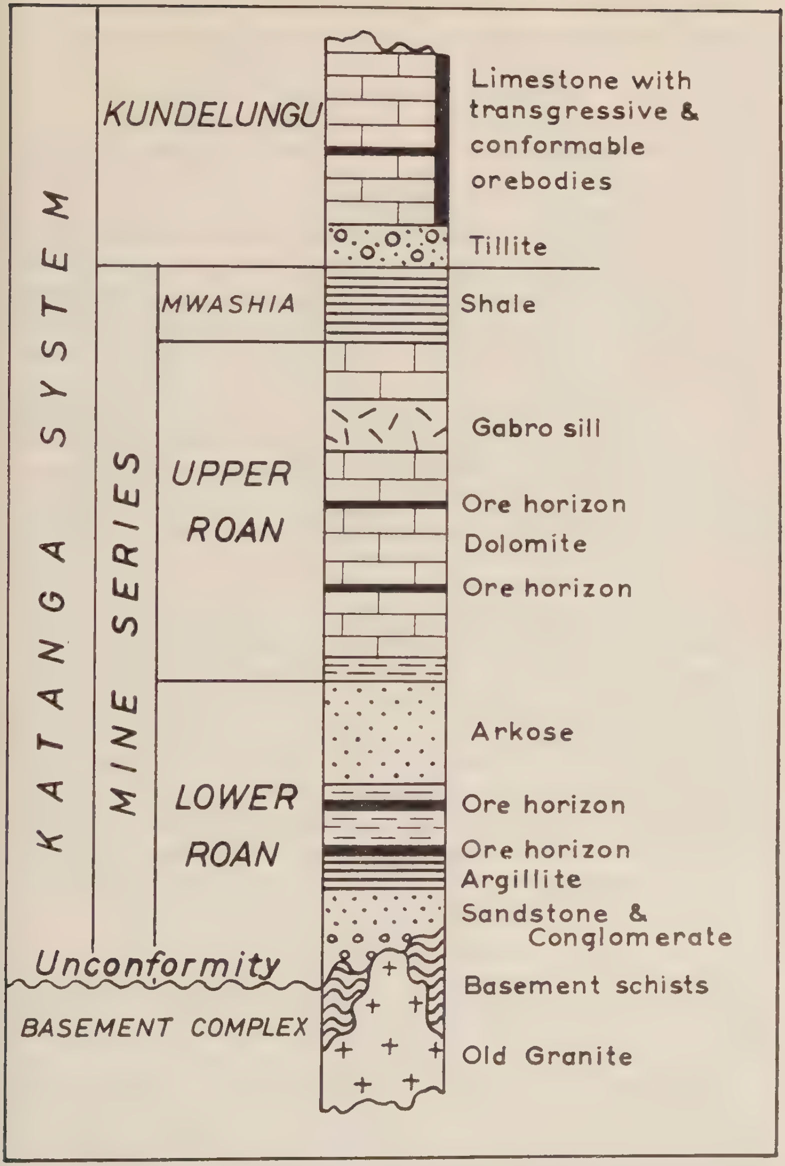

Fig. 7. Schematic geological column of the Northern Rhodesia–Katanga Copperbelt deposits

Kipushi, seems to be more reasonably explained on a hydrothermal epigenetic basis than by adopting Garlick's suggestion that disseminated syngenetic sulphides were dissolved and transported into fissures by groundwaters or during regional metamorphism. That there is clear evidence of minor lateral secretion of sulphides from the bedded deposits into fractures cannot be gainsaid, but for wholesale migration of the metals, including lead and zinc, no supporting criteria have been adduced.

Darnley (1960) may more closely approach the truth by advocating the essential rôle of hydrothermal solutions derived from an unexposed and probably deep-seated magmatic source, the ore solutions being introduced penecontemporaneously with the deposition of the Lower Roan sediments and continuing intermittently throughout the period of progressive burial and consolidation of the strata. He visualises that the main phase of sulphide mineralisation took place 'towards the end of the period when rock temperatures were high but before metamorphic recrystallisation had advanced sufficiently to eliminate differences in permeability governed by the original lithology'. Widespread potash metasomatism and tourmalinisation preceded mineralisation, which is often localised by carbonaceous quartzites laid down in channels. Darnley's conclusions are in keeping with evidence from Katanga suggesting that hydrothermal fluids of epigenetic origin reached favourable sites for ore deposition after the onset of tectonic deformation. Clearly, however, much more research is needed, including age determinations on galena from different ore horizons, before the genesis of these deposits is finally settled.

While admitting that some deposits of pyrite may be formed by the precipitation of iron sulphide in marine basins, due to adsorption, anaerobic bacterial sulphate reduction or the activity of biogenic hydrogen sulphide, I am not yet convinced that other metallic sulphides can accumulate sufficiently by these processes to produce economic mineral deposits. Secondary processes of diagenesis frequently account for local segregations of sulphides, notably galena and sphalerite in calcareous layers, but these rarely appear to be in workable quantities.

12. CONCLUSIONS

Since the present state of knowledge concerning the genesis of sulphide ores is still grossly inadequate, the following conclusions are no more than tentative.

1. Metallogenetic provinces are fundamentally due to inhomogeneities in the mantle and to the ascent of ore fluids along deeply penetrating crustal flaws. Once metals are incorporated in the crust they may eventually be involved in cycles of erosion, sedimentation, orogeny, granitisation and rejuvenation, the imprint of specific metals being indelibly stamped on individual metallogenetic provinces from early geological times.

2. The pattern of ore districts is often related to the disposition of crustal lineaments, the ore fluids rising along them from deep-seated magmatic sources.

3. Copper–nickel sulphide ores are genetically akin to basic igneous rocks of the gabbro–norite clan.

4. Many base-metal sulphide deposits are derived from residual hydrothermal solutions emanating from intrusive granitic plutons. Near these ore deposits the granitic rocks may contain syngenetic disseminated sulphides and abnormal trace amounts of the same metals within the lattices of receptive oxide and silicate minerals.

5. Current dissatisfaction in certain quarters with the magmatic hydrothermal theory of the origin of mineral deposits seems, in the main, to be without justification.

6. Granitisation may lead to the concentration of ore-forming metals within resistant country rocks, to their incorporation in hospitable silicates, or to their eventual segregation in mobile residual fluids.

7. Metamorphism in the presence of chemically active fluids may produce ore deposits, especially in open systems which facilitate the migration of metals into propitious low pressure zones such as fractures and the crests of folds.

8. Sulphide ores may be remobilised by hydrothermal solutions and deposited elsewhere to form 'secondary hydrothermal' or 'regenerated' ores.

9. Among hydrothermal solutions the ore-forming rôles of metamorphic and groundwater types seem to be subordinate to that of magmatic water.

10. Submarine exhalative sedimentary ores, such as those of Rammelsberg and Meggen in Germany, are probably not uncommon.

11. Sedimentary sulphide ores derived from the erosion of pre-existing mineralisation and deposited in a marine environment are apparently of minor importance, except possibly in the case of iron pyrites.

REFERENCES

Adams, F. D. 1934. Origin and Nature of Ore Deposits: an Historical Study. *Bull. geol. Soc. Amer.*, **45**, 375.

Andreatta, C. 1954. Über die Entstehung regenierter Lagerstätten durch Magmatismus und tektonische metamorphische Mobilisierung. *Neues. Jahrb. f. Min.*, f. 1953, 131.

Backlund, H. G. 1952. Some Aspects of Ore Formation, Pre-Cambrian and Later. *Trans. Edin. Geol. Soc.*, **14**, 302.

Barnes, H. L. 1959. The Effect of Metamorphism on Metal Distribution near Base Metal Deposits. *Econ. Geol.*, **54**, 919.

Barton, P. B., Jr. 1959. The Chemical Environment of Ore Deposition and the Problem of Low-Temperature Ore Transport. *Researches in Geochemistry*, New York, 279.

Bateman, A. & M. L. Jensen. 1956. Notes on the Origin of the Rhodesian Copper Deposits: Isotope Composition of the Sulfides. *Econ. Geol.*, **51**, 555.

Baumann, L. 1958. Tektonik und Genesis der Erzlagerstätte von Freiberg (Zentralteil). *Freiberger Forsch.*, **46**, 1–208.

Bilibin, Y. A. 1950. On Geochemical Types of Orogenic Zones. *XVIII Int. Geol. Congr., London*, **1** (2), 22.

Billingsley, P. & A. Locke. 1941. Structures of Ore Districts in the Continental Framework. *Trans. Amer. Inst. min. (metall.) Engrs.*, **144**, 9.

Boyle, R. W. 1959. The Geochemistry, Origin and Rôle of Carbon Dioxide, Water, Sulfur, and Boron in the Yellowknife Gold Deposits, Northwest Territories, Canada. *Econ. Geol.*, **54**, 1506.

Brown, J. S. 1950. *Ore Genesis. A Metallurgical Interpretation: an Alternative to the Hydrothermal Theory.* Thos. Murby, London.

Brummer, J. J. 1955. The Geology of the Roan Antelope Orebody. *Trans. Instn. Min. Metall., London*, **64**, 257.

Buddington, A. F. 1959. Granite Emplacement with Special Reference to North America. *Bull. geol. Soc. Amer.*, **70**, 671.

Burnham, C. Wayne. 1959. Metallogenic Provinces of the Southwestern United States and Northern Mexico. *Bull.* 65, *State Bur. Mines and Min. Resources, New Mexico Inst. Mining and Techn., Socorro, New Mexico.*

Cahen, L. *et al.* 1958. On a Correlation between the Common Lead Model Age and the Trace-Element Content of Galena. *Geochim. et cosmoch. Acta*, **14**, 134.

Crook, T. 1933. *History of the Theory of Ore Deposits.* Thos. Murby, London.

Darnley, A. G. 1960. Petrology of some Rhodesian Copperbelt Orebodies and Associated Rocks. *Trans. Instn. Min. Metall., London*, **69**, 137.

Davidson, C. F. 1960. Some Aspects of Radiogeology. *Liverpool and Manchester Geol. Journ.*, **2** (3), 311.

Deans, T. 1950. The Kupferschiefer and the Associated Lead–Zinc Mineralisation in the Permian of Silesia, Germany and England. *XVIII Int. Geol. Congr., London*, **7**, 340.

De Launay, L. & Urbain. 1910. Recherches sur la Metallogenie des Mineraux qui en Derivent. *Bull. Soc. géol. Fr.*, **10**, 789.

Den Tex, E. 1958. Studies in Comparative Petrofabric Analysis: The Broken Hill Lode and its Immediate Wall Rock. *Australasian Inst. Min. & Metall., F. L. Stillwell Ann. Vol.* **77.**

De Vore, G. W. 1955. The Rôle of Adsorption in the Fractionation and Distribution of Elements. *J. Geol.*, **63**, 159.

Dunham, K. C. 1952. Age-Relations of the Epigenetic Mineral Deposits of Britain. *Trans. geol. Soc. Glasg.*, **21** (3), 395.

———. 1959. Epigenetic Mineralisation in Yorkshire. *Proc. Yorks. geol. (Polyt.) Soc.*, **32**, 1.

——— & R. Phillips *et al.* 1958. The Chromiferous Ultrabasic Rocks of Eastern Sierra Leone. *Overseas Geol. Min. Res. Bull., Supp.* 3, 1.

Edwards, A. B. 1956. The Present State of Knowledge and Theories of Ore Genesis. *Proc. Australasian Inst. Min. & Metall.*, **177**, 69.

Ehrenberg, H., A. Pilger & F. Schröder. 1954. Das Schwefelkies-Zinkblende-Schwerspatlager von Meggen (Westfalen). *Monogr. der Deutsch. Blei-Zink-Erzlagerstätten, Nr.* 7. Hanover.

Emmons, S. F. 1904. Theories of Ore Deposition Historically Considered. *Bull. geol. Soc. Amer.*, **15**, 1.

Garlick, W. G. 1959. How the Copperbelt Orebodies Were Formed. *Horizon, Magazine Rhodesian Selection Trust Group* (Aug. 10).

Gavelin, S. 1955. Sulphide Mineralisation in the Skellefte District, Northern Sweden, and its Relation to Regional Granitisation. *Econ. Geol.*, **50**, 814.

Goodchild, J. H. 1918. The Evolution of Ore Deposits from Igneous Magmas. *Mining Mag., London*, **18** and **19.**

———. 1919. The Genesis of Igneous Ore Deposits. *Trans. Instn. Min. Metall., London*, **28**, 274.

Goodspeed, G. E. 1952. Mineralisation Related to Granitisation. *Econ. Geol.*, **47**, 146.

Goranson, R. W. 1931. The Solubility of Water in Granite Magmas. *Amer. J. Sci.*, **5** (22), 481.

GRAY, A. 1958. The Future of Mineral Exploration. (The Fourth Sir Julius Wernher Memorial Lecture.) *Trans. Instn. Min. Metall., London*, **68,** 21.

GREGORY, J. W. 1928. *The Elements of Economic Geology*. Methuen & Co. Ltd., London.

HILLEBRAND, J. R. 1954. A Suggested Source of the Thiophile Elements of the Tertiary Ore Deposits of the Southwest. *Econ. Geol.*, **49,** 863.

JENSEN, M. L. 1959. Sulfur Isotopes and Hydrothermal Mineral Deposits. *Econ. Geol.*, **54,** 374.

KING, HADDON F. 1958. Notes on Ore Occurrences in Highly Metamorphosed Pre-Cambrian Rocks. *Australasian Inst. Min. & Metall., F. L. Stillwell Ann. Vol.* **143.**

KNIGHT, C. L. 1957. Ore Genesis—The Source Bed Concept. *Econ. Geol.*, **52,** 808.

KONSTANTINOV, M. M. 1954. Near Future Tasks in the Investigation of Lead and Zinc Ore Deposits of Sedimentary Origin. *Izvestiva Akad. Nauk. S.S.R., Geol. Ser.* 1.

KRAUME, E. 1955. Die Erzlager des Rammelsberges bei Goslar. *Monogr. der Deutsch. Blei-Zink-Erzlagerstätten, Nr* 4. Hanover.

KRAUSKOPF, K. B. 1955. Sedimentary Deposits of Rare Metals. *Econ. Geol.*, **50** (1), 411.

————. 1956. Factors Controlling the Concentrations of Thirteen Rare Metals in Sea Water. *Geochim. et cosmoch. Acta*, **9,** 1.

————. 1957. The Heavy Metal Content of Magmatic Vapor at 600°C. *Econ. Geol.*, **52,** 786.

————. 1959. The Use of Equilibrium Calculations in Finding the Composition of a Magmatic Gas Phase. *Researches in Geochemistry*, New York, 260.

KULP, J. L., G. C. AMSTUTZ & F. D. ECKELMANN. 1957. Lead Isotope Composition of Peruvian Galenas. *Econ. Geol.*, **52,** 914.

LINDGREN, W. 1933. *Mineral Deposits*. 4th ed. McGraw-Hill Book Co. Inc., New York.

MOREY, G. W. 1922. The Development of Pressure in Magmas as a Result of Crystallisation. *J. Wash. Acad. Sci.*, **12** (9), 219.

OFTEDAHL, C. 1958. A Theory of Exhalative-Sedimentary Ores. *Geol. Fören. i Stockholm Forh.*, **80** (1), 1.

READ, H. H. 1948. Granites and Granites. *Mem. geol. Soc. Amer.*, **28.**

————. 1951. Metamorphism and Granitisation. *Trans. geol. Soc. S. Afr., Annex to* 54.

————. 1957. Metamorphic Geology: Reflections on its Past, Present and Future. *Journ. Madras Univ. Centenary Number*, **71.**

RINGWOOD, A. E. 1956. A Study of the Rôle of a Gas Phase in Segregation and Concentration of Trace Elements in a Magma. *Proc. Australasian Inst. Min. & Metall.*, **180,** 75.

RUSSELL, R. D. & R. M. FARQUHAR. 1957. Isotopic Analyses of Leads from Broken Hill, Australia. *Trans. Amer. geophys. Union*, **38,** 557.

SALES, R. & C. MEYER. 1951. Effect of Post-Ore Dyke Intrusion on Butte Ore Minerals. *Econ. Geol.*, **46,** 813.

SCHNEIDERHÖHN, H. 1949. *Erzlagerstätten*. 2nd ed. Stuttgart.

————. 1953. Genetische Lagerstättengliederung auf geotektonischer Grundlage. *Neues Jahrb. f. Min. f.* 1952, **47.**

————. 1954. La position génétique des gîtes métallifères post-Triassiques de l'Afrique du Nord Française. *XIX Int. Geol.; Congr., Algiers*, 1952, *Sec.*, **XII,** 73.

————. 1955. *Erzlagerstätten*. Stuttgart.

SHAW, D. M. 1954. Trace Elements in Pelitic Rocks. *Bull. geol. Soc. Amer.*, **65,** 1151.

————. 1957. Comments on the Geochemical Implications of Lead-Isotope Dating of Galena Deposits. *Econ. Geol.*, **52,** 570.

SLAWSON, W. F. & M. P. NACKOWSKI. 1959. Trace Lead in Potash Feldspars Associated with Ore Deposits. *Econ. Geol.*, **54,** 1543.

SPURR, J. E. 1923. *The Ore Magmas*.

STANTON, R. L. & R. D. RUSSELL. 1959. Anomalous Leads and the Emplacement of Lead Sulfide Ores. *Econ. Geol.*, **54,** 588.

STILLWELL, F. L. 1959. Petrology of the Broken Hill Lode and its Bearing on Ore Genesis. *Proc. Australasian Inst. Min. & Metall.*, **190,** 1.

SULLIVAN, C. J. 1948. Ore and Granitisation. *Econ. Geol.*, **43,** 471.

————. 1957. Classification of Metalliferous Provinces and Deposits. *Trans. Canad. Min. Inst.* (*Inst. Min. Metall.*), 333.

————. 1959. The Origin of Massive Sulphide Ores—in Symposium on the Genesis of Massive Sulphide Deposits. *Canad. Min. metall. Bull.*, **52,** 613.

TAYLOR, S. R. 1955. The Origin of some New Zealand Metamorphic Rocks as shown by their Major and Trace Element Composition. *Geochim. et cosmoch. Acta.*, **8,** 182.

TURNEAURE, F. S. 1955. Metallogenetic Provinces and Epochs. *Econ. Geol.*, **50** (1), 38.

TURNER, F. J. 1948. Mineralogical and Structural Evolution of the Metamorphic Rocks. *Mem. geol. Soc. Amer.*, **30.**

TUTTLE, O. F. & N. L. BOWEN. 1958. Origin of Granite in the Light of Experimental Studies in the System $NaAlSi_3O_8$–$KAlSi_3O_8$–SiO_2–H_2O. *Mem. geol. Soc. Amer.*, **74.**

WAGER, L. R. *et al.* 1957. Sulphides in the Skaergaard Intrusion, East Greenland. *Econ. Geol.*, **52,** 855.

WARREN, H. V. & R. M. THOMPSON. 1945. Sphalerites from Western Canada. *Econ. Geol.*, **40,** 309.

WHITE, D. E. 1955. Thermal Springs and Epithermal Ore Deposits. *Econ. Geol.*, **50** (1), 99.

————. 1957. Magmatic, Connate and Metamorphic Waters. *Bull. geol. Soc. Amer.*, **68,** 1659.

WILLIAMS, D. 1934. The Geology of the Rio Tinto Mines, Spain. *Trans. Instn. Min. Metall.*, London, **43,** 593.

WILSON, H. D. B. 1953. Geology and Geochemistry of Base Metal Deposits. *Econ. Geol.*, **48,** 370.

———— & D. T. ANDERSON. 1959. The Composition of Canadian Sulphide Ore Deposits—in Symposium on the Genesis of Massive Sulphide Deposits. *Canad. Min. metall. Bull.*, **52,** 619.

WISSER, E. H. 1959. Cordilleran Ore Districts in Relation to Regional Structure. *Canad. Min. metall. Bull.*, **52,** 34.

The Pleistocene Succession in the Middle Trent Basin

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ABSTRACT: The Pleistocene succession of the Middle Trent Basin is here reviewed in the light of recent research both in the Midlands and East Anglia. Two main glaciations, represented by boulder clays or outwash deposits, are identified and termed the Pennine Drift and Eastern Glaciation. The deposits of the Pennine Drift are highly weathered and deeply dissected where exposed, and evidence is presented for a considerable period of erosion between the accumulation of these deposits and the Eastern Glaciation. The main development of the Acheulean within the area would seem to belong to this time-interval. The Eastern Glaciation is seen to have been of a complex nature involving movement of ice both from the Pennines and from the east. To the Retreat stage of the Eastern Glaciation are assigned certain fluvio-glacial terrace gravels previously termed the Hilton Terrace.

The Drainage Changes, involving the courses of the Trent and the use by it of the Lincoln and Ancaster Gaps, are described in relation to the Pleistocene succession and the anomalous Nottingham–Newark–Lincoln course assigned to the Retreat stage of the Eastern Glaciation.

The terrace sequence and the contained fauna and culture is described and is seen to consist of the Hilton Terraces, with two major flats, assignable to the Retreat stage of the Eastern Glaciation, the Beeston Terrace probably assignable to the Last Interglacial and containing cultural material including fresh Levalloisian flakes and the Flood-plain Terrace. In so far as the area was not glaciated after the Eastern Glaciation the terraces are described as post-glacial.

1. HISTORY OF PREVIOUS RESEARCH

MUCH HAS BEEN WRITTEN on the Pleistocene deposits and the glacial history of the area though little original work has been published for many years.

The account by R. M. Deeley in 1886 still provides much of the basic material for a study of the area.

In 1712, Morton, in his *Natural History of Northamptonshire*, gave find details of Pleistocene mammalian remains from Bowdon Parva, and later in the eighteenth century Earl Ferrers (Nichols, 1794) described the succession on Shipley Hill. These and other early descriptions of the superficial deposits, though valuable as descriptions of exposures, were not, by reason of their date, recognised as referring to glacial deposits. The Geological Survey did not mark the Drift on their early maps, but nevertheless provided some account of the succession in the *Memoirs*. Hull, in the 1860 *Memoir* for the Leicestershire Coalfield, recognised the presence of Northern Drift, characterised by granite erratics, Eastern Drift with chalk and flints and Charnwood Drift. The local historians like Molyneux (1869) for Burton-on-Trent and J. B. Jukes (*in* Potter, 1842) for Charnwood Forest gave a description of the succession of deposits at certain localities, and, in the case of Jukes, some description of the different kinds and the areal extent of the drifts. Numerous accounts of the finding of mammalian remains in the river gravels were made in such antiquarian studies as Briggs's *History and Antiquities of Hemington* (1873), and in the numbers of the *Midland Naturalist*. J. Shipman described the terrace gravels of the Leen and of the Trent near Nottingham (1879, 1883). The mapping of Lincolnshire by the Geological Survey and the publication of several papers by Jukes-Browne (1879, 1885) provided the first detailed description of the glacial deposits for a neighbouring region. Jukes-Browne (1883, 1885b) also gave the first detailed account of the important drainage changes in the Trent Valley following Penning's observation on the former course of the Trent in 1878 and Ramsey's (1863) recognition of the anomalous transverse course of the Trent across the Keuper Marl dip slope between Nottingham and Newark.

Deeley, in his 1886 paper, described numerous exposures now overgrown, and provided a succession divided into Older, Middle and Newer deposits. Though this succession received criticism and amendment from Fox-Strangways (1899, 1903, 1905 and 1907), who mapped a large part of the Middle Trent for the Geological Survey, nevertheless his study provided the basis for many of the later papers on the area. His subdivisions, which often seem to be based on a local rather than a regional basis, give an undisputed succession of boulder clays, Early, Middle Pennine, Great Chalky and Later Pennine boulder clay. He also provided descriptions of the terrace gravels, termed interglacial, of the Trent and Dove. In 1896 (Bemrose & Deeley, 1896) the terrace succession south of Derby and its relationship to the boulder clays was described in greater detail. The Geological Survey, in their mapping of the area, published between 1903 and 1911, provided an accurate cover of the Drift deposits and distinguished between terrace and fluvio-glacial gravels. Fox-Strangways stressed the importance of local variations and described in detail the exposures of the Wreak and Soar Valleys.

In 1929, T. I. Pocock described the terraces of the Trent from above Lichfield to beyond the Lincoln Edge and distinguished six terraces. He related the terraces to the boulder clay spreads to the west of Burton-on-Trent and to the east of the Lincoln Gap and gave an account of drainage changes during the Pleistocene, which he again dealt with in a later paper (Pocock, 1954). H. H. Swinnerton, in papers in 1937 and 1948, summarised the succession and gave a full account of the drainage development. Clayton, in 1953, related the terrace succession to the west of Derby to that of the West Midlands. The mapping of the area round Burton-on-Trent by the Geological Survey and the publication of the *Memoir* in 1955, provides the most recent detailed study and distinguishes an Early boulder clay of western origin, a Chalky boulder clay with flinty outwash gravels and a Pennine or Irish Sea Drift less dissected than the Chalky boulder clay and exhibiting overflow channels and other glacier marginal phenomena. The *Memoir* also distinguishes fluvio-glacial from post-Irish Sea Ice terrace gravels in refutation of Pocock & Clayton, who had described them as true river terraces.

2. RECENT RESEARCH OUTSIDE THE AREA

Work affecting the area has been undertaken in the surrounding areas: in the West Midlands by Tomlinson, Wills and Shotton; in Northamptonshire by Hollingworth & Taylor and in East Anglia by Baden-Powell, West & Donner. Though Clayton correlated his work with that of the West Midlands, the most recent work by Shotton (Shotton, 1953) in the Leamington–Coventry area and by West & Donner on the East Midlands and East Anglia (West & Donner, 1956), both of which fundamentally deal with the glacial succession as represented by boulder clays rather than with a terrace succession based on heights above present-day alluvium, has necessitated a complete re-appraisal of the glacial succession in the Trent basin.

This recent research, combined with the application of pollen analysis to interglacial deposits, and, in particular, its application to such sites as Hoxne in East Anglia (West, 1954, 1956), where human industries are associated with an interglacial deposit, has enabled a more coherent picture to be presented of the whole Pleistocene succession in Great Britain, as has been effected by W. B. R. King in 1955. Recent work on the continent, particularly by Woldstedt (1950) and Van der Vlerk (1953), has freed the Pleistocene geologist, and even more so the archaeologist, from a dependence for their continental correlations on the outmoded Alpine sequence of Penck & Bruckner, or the extra glacial terrace succession of the Somme, based in its turn on the Alpine terminology.

3. THE PLEISTOCENE SUCCESSION IN THE MIDDLE TRENT BASIN

It has been possible to differentiate within the area two series of boulder clays and associated deposits, representing two main glacial episodes succeeded by the deposition of the terrace gravels of the Trent and its tributaries.

The sequence of Pleistocene deposits that can be recognised is as follows in descending order of age.

NEWER DRIFT
- River Terraces.
  - Floodplain Terrace—Trent No. 1—divisible into two stretches:
    - (a) below Beeston; 5–10 ft. above alluvium
    - (b) above Beeston; below modern alluvium
  - Beeston Terrace

OLDER DRIFT
- Lower Hilton Terrace
- Upper Hilton fluvio-glacial terrace gravels
- Outwash gravels of retreating Pennine Ice
- Deposits of Eastern Glaciation
  - Chalky boulder clay and associated outwash gravels
  - Middle Pennine boulder clay
- Long time-interval
- Pennine Drift
  - Skegby outwash gravels
  - Early Pennine boulder clay

(a) Pennine Drift

Deposits assignable to the Pennine Drift (Fig. 1) constitute the oldest deposits in the area and can be distinguished as such either from their position beneath later deposits, their degree of weathering or their height above later deposits indicative of erosion subsequent to their deposition. Their scanty nature is due to their widespread erosion during the succeeding interglacial and their destruction and incorporation into the ground moraines of the ice-sheets of the Main Eastern glaciation.

The best exposures occur beneath the later boulder clays. At Kilby Bridge (42 (SP) 613972) nine feet of red loamy clay with a few quartzite pebbles and an occasional fragment of Keuper sandstone and Charnwood erratics (mostly Mountsorrel granites) is found stratified beneath three feet of yellow-buff chalky boulder clay and lies directly above the Lias clay. Deeley describes various exposures of the Early Pennine boulder clay from the valley of the Wreak, where it is found stratified beneath Quartzose Sand (see p. 290) and later boulder clays. At Thrussington (Deeley, 1886, 443) he records upwards of thirty feet of red clay marked by an absence of eastern erratics. Harmer (Harmer, 1928, 144) described a deposit at

Leicester Forest where Chalky boulder clay rested on an eroded surface of purple Triassic Drift containing boulders of Charnwood and Carboniferous erratics. Similar exposures were described from Thurmaston. Other exposures were described by Fox-Strangways from the Wreak Valley. A feature of all the observed exposures is the markedly local composition both with regard to the clay matrix and the contained pebbles. A high-level gravel interpreted by H. H. Swinnerton as outwash gravel of the retreat of the Pennine ice is found at Skegby on the Sutton plateau above the 500 foot contour and at Kirk Ireton, where the gravel is mainly composed of quartzite pebbles with a very occasional Pennine erratic. At Blackwall, Clayton (1951), found a similar outwash gravel lying at some 260 to 350 feet above the adjacent valley floor.

From south of the region in Northamptonshire an older boulder clay, brown in colour, free from flints but rich in Bunter and Jurassic erratics, is

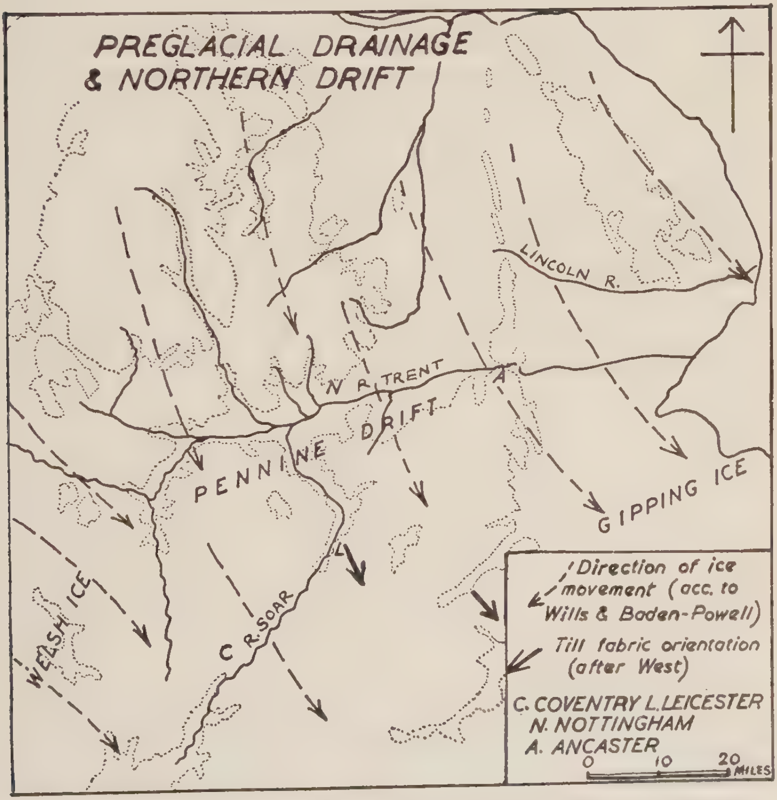

Fig. 1. Pre-glacial drainage and Northern Drift. Contoured 200 feet and 600 feet

found underlying the Chalky boulder clay (Hollingworth & Taylor, 1946). It would seem that this older boulder clay corresponds with that from Kilby and from the Wreak Valley, all of which are marked by a strong Bunter pebble erratic content. To the south of Northamptonshire these deposits have been described by Arkell (1948, 194) as belonging to his Northern Drift. As in the Middle Trent region the drift here is thin, very weathered where exposed, and of a markedly local composition.

West & Donner examined the Pennine Drift at Kilby and Brigstock in Northamptonshire (42 (SP) 953850) and found that the direction of movement was from the north of north-west. This line of movement confirms that postulated from the erratic content of boulder clays by Baden-Powell (1948, fig. 1), who also suggested that the Pennine ice was the upstream part of the ice-sheet depositing the Lowestoft boulder clay. Hollingworth & Taylor (1946, 230) also suggested a similar direction of ice movement.

Several other exposures of 'gravelly drift' found in isolated localities and described by the older authorities, though of probable Pennine ice derivation, cannot be considered as such until the erratic content can be proved to show northern derivation, since many Bunter exposures have a similar appearance to outwash gravels. There is a further problem with regard to the lower boulder clays that they could date from the succeeding glacial period, when the Pennine ice appears to have advanced across the Trent before the advance of the Main Eastern ice. The lower boulder clay at Shelton Lock (43 (SK) 376314), which Deeley (1886, 448) assigns to his Middle Pennine boulder clay, could come into this class, though there is no means of proving the age of these residual patches of boulder clay, which being of Pennine derivation, exhibit the same direction of ice movement. It is only where signs of definite weathering as at Brigstock or the presence of possible interglacial deposits as in the Wreak Valley can be proved, that there is a surety of age.

(b) The Interval between the Pennine and the Eastern Glaciations

No river gravels have yet been found that date from this period. Whatever deposits were laid down must have been destroyed and incorporated into the deposits of the Eastern Drift. The erosion subsequent to the deposition of the gravels at Skegby and Blackwall gives some measure of the antiquity of the deposits, though unfortunately no deposits are found adjacent to the Main Eastern deposits to allow assessment of the time-interval.

Deeley (1886, 445–8) described a deposit which he called Quartzose Sand, which he found overlying the older boulder clay near Avenue Plantation and at Aylestone and interbedded between his two earlier Pennine boulder clays along the Wreak Valley. Fox-Strangways also described this deposit which is often conglomerated and consists of false bedded sand and gravel, and he gave details of a section at Rotherby, where about five feet of stratified clayey sand is found above twenty-one feet of laminated brick clay and twelve feet of hard tough red boulder clay and under eight to twelve feet of Chalky boulder clay (Fox-Strangways, 1903, 45). In connection with the Quartzose Sand the arguments of Carruthers (1953) as to the undermelt of static ice-sheets and the resulting stratification of deposits that can be mistaken for deposits of different glacial phases, must not be ignored.

Hollingworth & Taylor in Northamptonshire found between two boulder clays what they termed Mid-glacial gravels, which they interpreted as being outwash or old valley gravels consisting predominantly of a Bunter and local content (Hollingworth & Taylor, 1946, 231). Shotton mapped the Baginton–Lillington gravels of Warwickshire (Shotton, 1953, 222), which appear to belong to the phase immediately preceding the Main Eastern glaciation and which from their slope to the north-east suggest the drainage of the area to the Trent during the interglacial. It is possible that many of the exposures of Quartzose Sand as described by Deeley (1886, 454), as at Leicester Abbey, could be related to the north-eastern continuation of the Baginton–Lillington sands and gravels.

(c) The Eastern Glaciation

The deposits of the Eastern Glaciation (Fig. 2) represent the most important glacial deposits within the region. They are represented by thick spreads of Chalky boulder clay found south of the Trent over the Nottinghamshire–Leicestershire Wolds and over the larger part of Northamptonshire. At Hallaton, in Leicestershire, these deposits attain a thickness of over 150 feet. As compared with the older boulder clay, where the clay matrix is red and derived predominantly from the Keuper Marl, the clay matrix of these deposits is grey, blue or yellow in colour, derived in the main from the Jurassic and Cretaceous clays. The boulder clay is charged with eastern erratics of which the most noticeable are the flints, though Chalk and Jurassic rocks and fossils are common (see Appendix I).

Though this Chalky boulder clay, which represents a movement of ice from the east of the region over the Cretaceous rocks of East Anglia and Lincolnshire, is the chief element in this glacial phase, it is not the only one. The evidence of Jowett & Charlesworth (1929, 316), from Derbyshire, indicates that during this period the 'Derbyshire Dome was completely overridden with the possible exception of small nunataks'. The actual presence of Eastern ice spreading from a continental mass suggests that this was the most important of the glacial phases. This being so, it is to be expected that the native Pennine ice-sheet would be the first to overspread the Midlands, later to be displaced by the more powerful ice-sheet coming from the east. Shotton (1953, 253) described how the berg-dropped erratics in the Wolston Series change from a Bunter suite below to a flint-rich assemblage above, as the impounding Pennine glacier at the northern end of Lake Harrison was pushed westward by the Eastern ice.

The Pennine ice, though displaced south of the Trent, blocked the advance of the Main Eastern ice to the north and west. This was suggested by Harmer (1928. 138) to explain why the Main Eastern ice climbed the Marlstone ridge of Leicestershire and Rutland to a height of 600 to 700 feet, rather than spreading farther to the north and west. The most northerly exposure of Chalky boulder clay is that found at Chellaston (SK 387301) where lithological analysis (see Appendix I) showed that 52% of the contained pebbles consisted of Cretaceous erratics (35% chalk, 17% flints, mostly grey of the Lincolnshire type), 26% Triassic (Bunter pebbles 15%) and 9% proven Jurassic erratics, in a ten-foot deposit of brown boulder clay. The writer has picked up Eastern erratics north of the line

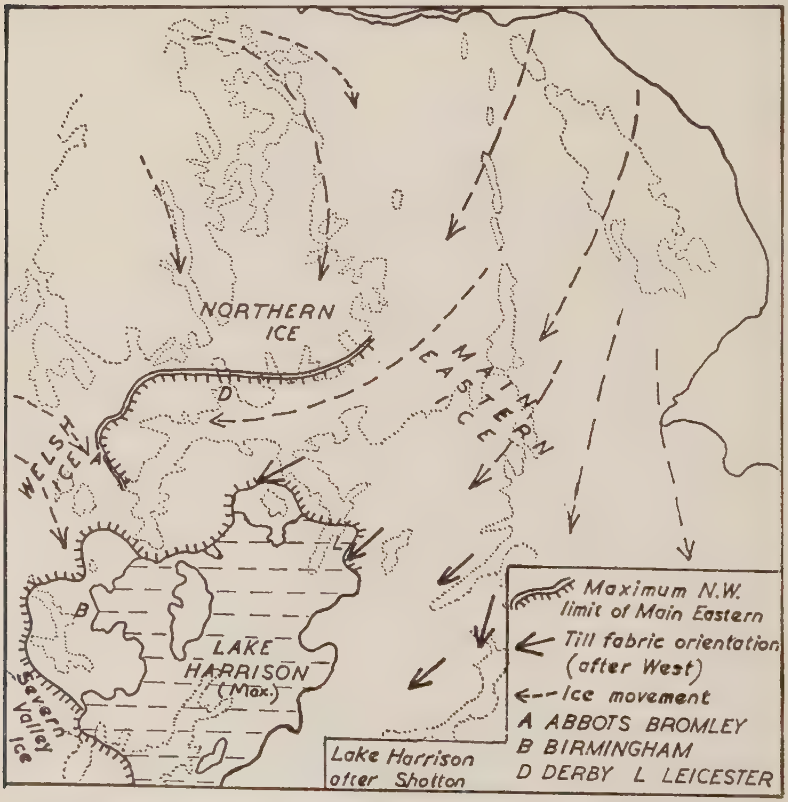

Fig. 2. Eastern Glaciation—maximum extent. Contoured 200 feet and 600 feet

indicated by Clayton (Clayton, 1953, fig. 1); Cretaceous and Jurassic erratics being found in the neighbourhood of Kirk Langley (SK 290380), whilst at Brailsford (SK 254417), at just under 500 feet, an exposure of poorly sorted gravels, most quartzites, but with some flints, would seem to indicate the outwash gravels of the most northerly extent of the Main Eastern ice. The westerly extent of the Main Eastern ice-sheet is indicated by the Geological Survey in their recent mapping of the glacial sands and gravels around Abbots Bromley and Kingston (see Fig. 1, 2). At Hanbury Woodend (SK 160260, Harmer, 1928, 145), Stockwell Heath and Drainton (Mitchell & Stevenson, 1955, 78) this outwash gravel covers deposits of older boulder clay with a Triassic matrix.

The Trent Valley thus represented a glacial contact zone during this period with the Main Eastern ice flanked against the Pennine ice to the north and west. The evidence of Sabine (1949) on the source of the drifts of Northants suggests that the Eastern ice moving across the Trent basin incorporated some of the material of the Pennine ice. From Argyle Street, Derby, an exposure of Chalky boulder clay showed both Eastern and Pennine erratics (Fletcher, 1891). This intermingling of ice-streams was also noted by Swinnerton (1948, 76). West & Donner (1956) have indicated from their till-fabric analysis that the ice in the Trent Valley was moving from nearly due east, around Charnwood from 30° north of east, and over Northants from 15° east of north. This line of movement is reflected in the scarcity of Jurassic erratics at Chellaston compared with exposures south of the Trent as at Mount Sorrel and Kilby (23% Jurassic erratics), and the preponderance of cherty grey flint derived from Lincolnshire compared with the larger number of black flints from exposures south of the Trent. West & Donner have related the ice movement over the East Midlands to the ice movement which left behind the Gipping boulder clay in East Anglia. This being so, the Pennine Drift–Eastern Glaciation time-interval can be correlated with the interglacial lake deposits of Hoxne, which in their turn can be correlated on the basis of the contained flora with 'Great Interglacial' deposits elsewhere, including those of Nechells in the Birmingham district which have been assigned by Shotton (Shotton, 1953, 240) to the interval between the First and Second Welsh Glaciation. (See also Duigan, 1956.)

(d) The Retreat of the Eastern Glaciation Ice-Sheets and Resultant Drainage Changes

Linton (1951) suggested that in pre-glacial times a proto-Trent flowed due east to the Lincolnshire coast. This idea was hinted at by Irving in 1876, and given full expression (see Fig. 1) by Swinnerton (1937), who postulated easterly flowing Ancaster and Lincoln Rivers, though the Ancaster River was shown as extending westwards only as far as Nottingham. Shotton's

(1953) plotting of the subdrift contours of the Avon Valley has indicated that the Warwickshire and Worcestershire Midlands drained to the Trent by means of a much extended Soar, which means that the Trent must have been a fairly large river in pre-Main Eastern times. The main gap at Ancaster lies at about 180 feet above sea-level, which, from the height of the highest possible terraces of the mid-Trent around Derby at a little over 220 feet, suggests that the Trent in pre-Eastern Glaciation times was a mature stream,[1] its course lying across the present Vale of Belvoir. The advance of the Northern, Main Eastern and Severn Valley ice-sheets have been shown by Shotton (1953) to have impounded a lake over the south-west Midlands (the old Bredon–Soar Valley) which he called Lake Harrison. The formation of the present Avon drainage, Shotton suggested, is largely due to the rapid erosion of these thick lake deposits by water from the melting north-eastern ice.

It is to this period of melt of the ice-sheets that we have to look for the great drainage changes in the Trent Valley and the initiation of the river terraces. On Wilford Hill at 230 to 240 feet is found a pebbly gravel, consisting, according to the description of the Geological Survey, mostly of Triassic material (Lamplugh & Wright, 1908). In the cuttings for gas mains made for a new housing estate in 1954, at just a little over 225 feet, over two feet of fairly fresh Chalky boulder clay were exposed. Unfortunately, no exposure has shown the relationship between the pebbly gravel, interpreted by Lamplugh & Wright as being boulder clay due to its contortions, and the lower Chalky boulder clay. The gravel was interpreted by Swinnerton (1948, 77–9) as being outwash gravel of a melting Pennine ice-sheet and similar exposures of gravelly drift were mapped by him at Bestwood, Sutton-in-Ashfield, Red Hill, Arnold, Annesley and Larch Farm, Blidworth. All are marked by their preponderantly local make-up and numerous concretions, most marked in the Blidworth Stones.[2] To the south of Blidworth the gravels are found at around 400 to 450 feet, whilst boulder clay caps the higher ground up to and over 500 feet. This would indicate the later date of the gravel and its probable origin as the glacial outwash of a melting Pennine ice-sheet. The presence of gravels at Colwick Wood, just north of the Trent trough, of a similar composition as those on Wilford Hill suggests that at that time the deep Trent trough was not in existence and that the meltwaters of the Pennine ice swept over a shallow valley, partly covered as at Wilford Hill with Chalky boulder clay.

The meltwaters of the Pennine ice would have greater erosive power than the meltwater of the Main Eastern ice left stranded as stagnant blocks due to the absence of a highland mass to the east. The low-lying nature of the landscape would suggest such a stagnant block over the Vale of Belvoir.

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[1] View expressed in a forthcoming study of the physique of the East Midlands by K. M. Clayton.

[2] Personal communication from Professor H. H. Swinnerton.

The Trent Valley when free from ice would be covered by thick deposits of unconsolidated ground moraine, which would be quickly eroded and the valley re-established. The continued melt of water during the summers would quickly erode the boulder clay, which added to by the ablation moraine of the shrinking ice would result in a rapid build-up in the valley of fluvio-glacial or outwash gravel. It has been shown by Flint (1947, 137) that the continued melting of a highland mass of ice results in terracing in the valleys, since 'the shrinkage creates a settling basin' in which the sediment is deposited and the meltwater passing over the older outwash choking the valley is overloaded, and erodes, rather than adds to the outwash. This terraced outwash mass is represented in the Middle Trent Valley by the upper levels of the Hilton Terrace.

Such high-level 'terrace' gravels are not found to the east of Long Eaton. Swinnerton (1937, 5) suggested that the gravels capping the low hills west

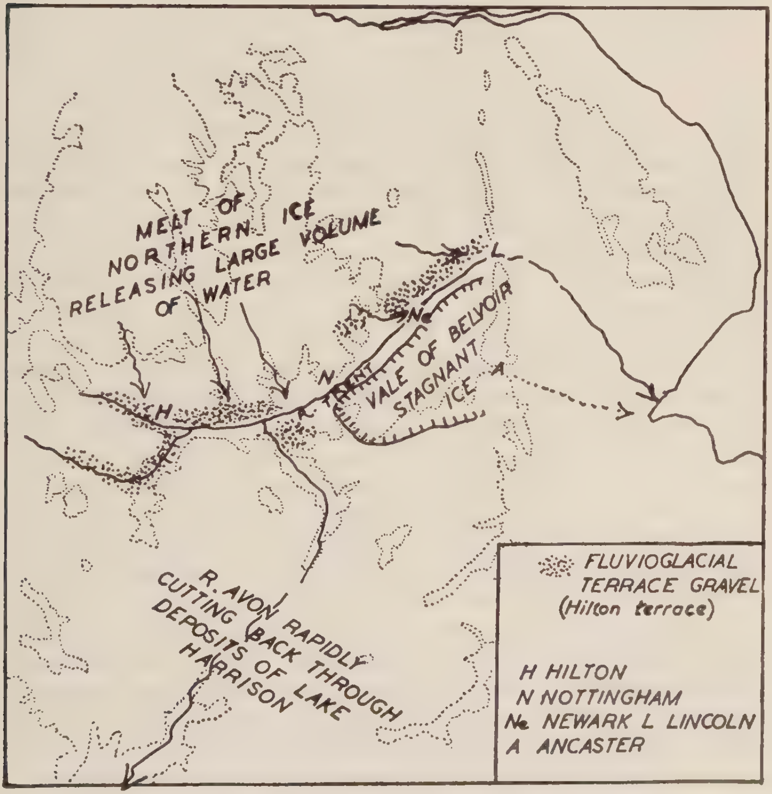
MELT OF NORTHERN ICE RELEASING LARGE VOLUME OF WATER
VALE OF BELVOIR STAGNANT ICE
R. TRENT
H
N
Ne
L
A
R. AVON RAPIDLY CUTTING BACK THROUGH DEPOSITS OF LAKE HARRISON
FLUVIOGLACIAL TERRACE GRAVEL (Hilton terrace)
H HILTON
N NOTTINGHAM
Ne NEWARK L LINCOLN
A ANCASTER

Fig. 3. Retreat stage of Eastern Glaciation. Contoured 200 feet and 600 feet

of Lincoln, in the vicinity of Eagle, represent similar outwash gravels to those south of Blidworth, the meltwaters probably escaping via the Lincoln Gap. From the heights of the gravels at Eagle and west of the gap at Heighington he suggested that the gradient was of the order of ten feet per mile and that the 'concentration of flow of water to this point established a strong current of water towards it'. If the Vale of Belvoir was covered by stagnant ice, the meltwaters of both this ice and that from the Pennines would be forced north-east of the ice over the Vale of Belvoir and would thus initiate the anomalous course of the Trent between Nottingham and Newark, the water escaping by means of the deepened Lincoln Gap. This would explain the trend of the river gravels from Newark to Lincoln, first noticed by Penning in 1878, the absence of Hilton 'terrace' gravels east of Long Eaton and the cutting of the Trent trench. The escape of water to the Lincoln Gap would also mean a certain steepening of gradient of the pre-glacial Trent and a downcutting, which is possibly that clearly separating the Upper and Lower Hilton Terraces.

4. THE RIVER TERRACES

The ice-sheets of the Eastern Glaciation were the last to encroach on the area, though the cold conditions brought about by later glacial phases were manifested in certain periglacial features. All the terraces are thus post-glacial in that sense and their dating is dependent on the date of the Main Eastern Glaciation, which it has been shown correlates with the Wolston series of Shotton, the Gipping of Baden-Powell and the Second Welsh of Wills.

One noticeable feature of the terraces is their position on the north side of the Dove and the Trent below Alrewas. All contain flints indicative of the erosion of the Eastern Drifts, though in all cases Bunter pebbles predominate amongst the gravel. The Geological Survey have distinguished two terraces (Mitchell & Stevenson, 1955), Pocock six (1929) and Swinnerton (1937) two, one of which he named the Beeston terrace and which is the same as the Second Terrace of Pocock and the Geological Survey, and the other the Flood-plain Terrace. To these two Clayton (1953) added the Hilton Terrace. Clayton claimed that all these terraces grade to a falling sea-level and so can be correlated with the Avon series of Tomlinson on the basis of height above the alluvium. He correlated the outwash gravel of Wilford Hill with Terrace No. 5 of the Avon. Though from Tomlinson's (1935) evidence, No. 5 would appear to date from the Retreat stage of the Eastern Glaciation, the height correlation cannot be advanced due to the different nature of the deposit. The Middle Trent Terraces cannot be correlated on a height basis alone, since they are away from the immediate effect of the rise and fall of sea-level. Though sea-level changes are universal, their effect is not, and both King (1950) and Zeuner (1945) have demonstrated the distinction between the middle and lower courses of a stream, and between climatic and thalassostatic terrace flats.

(a) The Hilton Terraces

The Hilton Terraces comprise all those gravels mapped by the Geological Survey as fluvio-glacial gravel and are found on the north side of the Dove from Uttoxeter to Aston-on-Trent and along the north side of the Trent (Fig. 3). Deeley called them high-level terraces, which he described in detail near Weston (Bemrose & Deeley, 1896, 500–5), where he claimed three terraces, whose upper escarpments were obliterated by solifluction, and he suggested they were formed while the river was clearing away the glacial deposits. Clayton (1953, 198) concluded that all the deposits mapped as fluvio-glacial gravel are the remnants of a true river terrace, which he named the Hilton Terrace and divided into an Upper and Lower Terrace, the Upper with a maximum for the aggradation of about ninety feet above the alluvium, the Lower with wide flats about forty-five to sixty feet above the alluvium. Mitchell & Stevenson in 1955 refused to accept the fluvio-glacial deposits as terraces and plotted the height range of the gravels to illustrate their lack of uniform height. This lack of accordance to a uniform height range could of course be explained away by the fact that there is more than one terrace. Armstrong (1939) suggested that the gravels are of subglacial origin and described the sections from Hilton where he distinguished three zones: A, a zone of ploughed-up Keuper Marl and gravel with the marl in lumps, separated by a band of sand from zone B which is similar to A but less compact, and zone C, which exhibited excessive contortion 'suggesting lateral pressure, or collapse under the influence of waterlogging and melting ice and snow'. Armstrong also found that the size of the flint contents became progressively smaller due to breaking down from zone A to C. On archaeological evidence alone and a comparison with the material at Cresswell, Armstrong suggested that the Hilton section represents at least two glacial phases.

It has been possible to study the Hilton Terraces in some detail around Hilton and Willington. It is clear in the field that there is a marked gravel flat with a noticeable riverward bluff, seven to twelve feet high. This is well seen in the neighbourhood of Swarkeston where levelling for an archaeological excavation showed this flat to be a little under sixty feet above the level of the alluvium. This same flat is well seen on the north of the road from Swarkeston to Willington, whilst from Willington to Hilton the road (B5009) runs along a lower flat at thirty to forty feet above the alluvium and a riverward bluff can be clearly seen to the immediate south of the road. In the vicinity of Willington (Fig. 4) at two gravel pits, north and south of the railway line, it was found that the upper flat has its base at

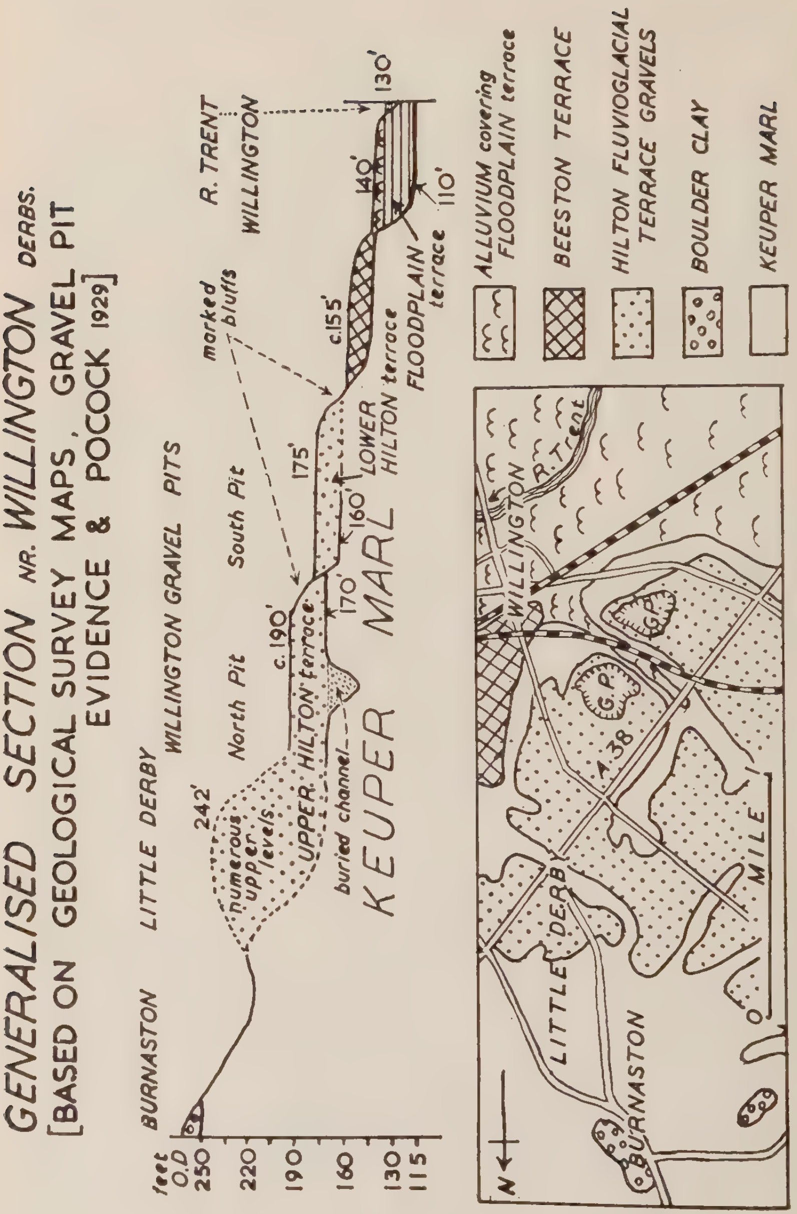
GENERALISED SECTION NR. WILLINGTON DERBS.
[BASED ON GEOLOGICAL SURVEY MAPS, GRAVEL PIT EVIDENCE & POCOCK 1929]
feet O.D
250
220
190
160
130
115
BURNASTON
LITTLE DERBY
WILLINGTON GRAVEL PITS
North Pit
South Pit
R. TRENT
WILLINGTON
242'
numerous upper levels
UPPER HILTON terrace
buried channel
c.190'
170'
175'
160'
marked bluffs
c.155'
LOWER HILTON terrace
140'
130'
110'
FLOODPLAIN terrace
KEUPER MARL
ALLUVIUM covering FLOODPLAIN terrace
BEESTON TERRACE
HILTON FLUVIOGLACIAL TERRACE GRAVELS
BOULDER CLAY
KEUPER MARL
N
BURNASTON
LITTLE DERBY
A 38
G.P.
G.P.
WILLINGTON
R. Trent
0
1 MILE

Fig. 4

around 170 feet, forty feet above the level of the river whilst the lower flat has its base at around 160 feet. The flats are separately based, though the surface of the lower flat lies above the base of the upper flat. These two flats are the only clearly distinct levels in the vicinity. The fluvio-glacial gravels have a wide height range, over 60 feet to the north of Willington from 242 feet at Little Derby to 165 feet at Willington south gravel pit. Pocock (1929) claimed two upper flats above the one at sixty feet above the alluvium.

As regards lithology (Appendix 1), samples from Hilton and both Willington pits showed that Bunter pebbles in all cases form over 70% of the total gravel, flint mostly of the cherty grey variety is the next most important element, whilst Derbyshire erratics are less numerous. Besides the gravel large lumps of boulder clay are found, brown and grey in colour, often with nuggets of chalk still extant. This suggests that the material is predominantly derived from the erosion of the Eastern Drift. In contrast, the later flood-plain gravels analysed at Swarkeston in the same area have Derbyshire erratics as the second most important element, Bunter pebbles being the first. Of the two Willington pits, the lower pit showed a smaller content of flint.

The exposures described by Armstrong are now filled in, though six to ten inches of the seventeen-foot section at Hilton were still visible in 1953, when the contortions described by Armstrong were observed. The form of these contortions suggest some form of cryoturbation during a succeeding glacial phase, when the area was subjected to periglacial conditions. The exposures of gravel are at all times variable, which illustrates the danger of giving generalised pictures. A constant feature at Willington was that contortions were present in the bottom half of the lower pit (Fig. 5) but not in the exposures of the upper pit. The sorting of the gravel varied, though it was found that the coarsest gravel occurred towards the top of the section of the upper pit and at the base of the lower pit. The sand and gravel often shows torrent bedding, whilst sand partings are numerous. This, combined with the often large size of the contained pebbles and the presence of boulder clay erratics, all point to the gravels being laid down by vast volumes of heavily charged water able to erode quickly the Chalky boulder clay. At the upper Willington pit, a steep-sided channel was encountered, incised nineteen feet, six inches into the underlying Keuper Marl and filled with sand, which must represent a channel cut by rapid meltwater and later buried.

Everything about the lithology and form of the Hilton Terraces confirm the opinion expressed above that they are outwash aggradation terraces of the melting ice of the Eastern Glaciation. The downcutting between the two marked lower flats could be due to the effects of the rapid cutting of the Trent trench from Nottingham to Newark working back to the Middle

Trent. The even bedding and sorting of the upper parts of the Lower Hilton flat, as seen at Willington and Hilton, indicate an amelioration in the climate and an approach to interglacial conditions.

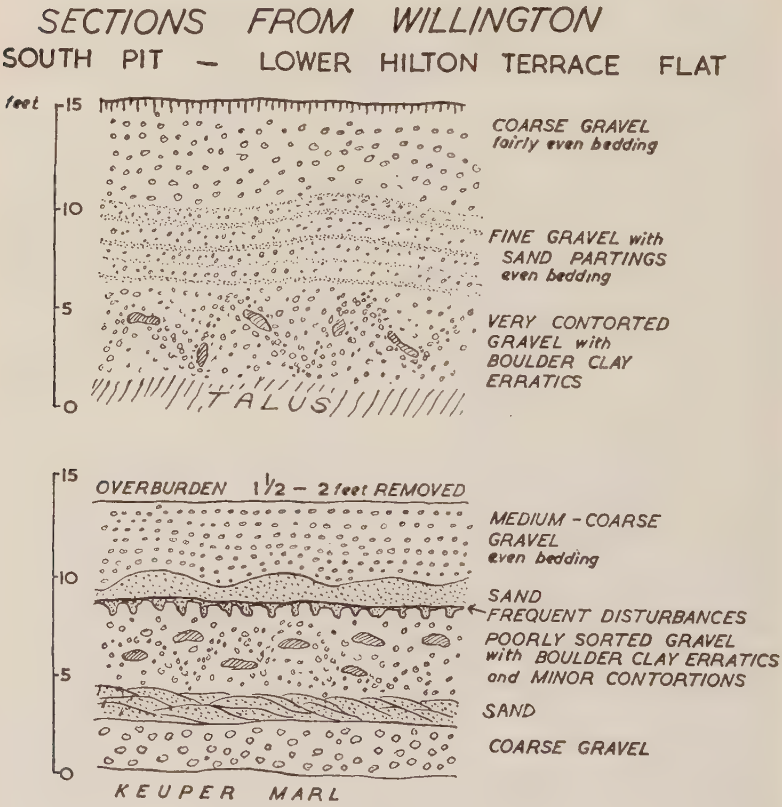
SECTIONS FROM WILLINGTON
SOUTH PIT — LOWER HILTON TERRACE FLAT
feet
15
10
5
0
COARSE GRAVEL fairly even bedding
FINE GRAVEL with SAND PARTINGS even bedding
VERY CONTORTED GRAVEL with BOULDER CLAY ERRATICS
TALUS
15
10
5
0
OVERBURDEN 1½ – 2 feet REMOVED
MEDIUM-COARSE GRAVEL even bedding
SAND
FREQUENT DISTURBANCES
POORLY SORTED GRAVEL with BOULDER CLAY ERRATICS and MINOR CONTORTIONS
SAND
COARSE GRAVEL
KEUPER MARL

Fig. 5

Palaeolithic artifacts have been found in the gravel pits of the Hilton Terraces. They comprise Clactonian flakes and Early and Middle Acheulean hand-axes. The bulk of the material is very heavily rolled and none is fresh: it would be unwise to date the gravels from these contained artifacts whose rolled condition suggests derivation from the preceding interglacial. The noticeable absence of Levallois flake-forms and later Acheulean hand-axes suggest that a dating of the gravels to the retreat stage of the Main Eastern Glaciation is not at conflict with the archaeological evidence from elsewhere. The absence of faunal remains, with the exception of a bone of

Bos primigenius of dubious derivation, is again in accord with the gravels being fluvio-glacial gravel terraces rather than more normal river terraces.

(b) The Beeston Terrace

The Beeston Terrace is well developed as a topographical feature on the north side of the Dove, on the south side of the Derwent below Derby, on both sides of the Trent from Rugeley to Burton and on the north side from Willington to Beeston, and on the south side to the east of Nottingham. By means of long profiles Swinnerton (1937) has shown that the old river gravels that mark the course of the Trent from Newark to Lincoln belong to this same aggradation, as do the gravels at Allenton, which have sometimes been given independent terrace status (Shotton, 1953, 237).

It would appear from the evidence available near Willington that the Beeston Terrace is independent of the lower fluvio-glacial gravels, the base of the Lower flat being separated from the top of the Beeston Terrace by a strip of Keuper Marl. For the region to the west of Burton-on-Trent, Mitchell & Stevenson (1955, 92) found 'the deposition of the latest fluvio-glacial gravels to have been contemporaneous or only slightly earlier than the formation of the Second Terrace to judge by difference of level'.

Lithologically (see Appendix I) the Beeston Terrace is very similar to the Hilton gravels with flints being the second most important constituent. At Beeston the surface of the terrace lies thirty to thirty-five feet above the alluvium, at Willington twenty feet and at Rugeley fifteen feet (Clayton, 1953, 202). At the only available sections at Beeston (SK 528372) and Bassingfield (SK 625377), where the gravel is between twelve and fourteen feet in thickness, a medium-sorted sand and gravel is found, with some clay in pockets at Bassingfield. Contortions have been observed in the upper surfaces at Spring Close (Shipman, 1879), Gamston, Lenton (Blake, 1906, 32) and Beeston, where the top two feet are affected and appear to postdate the aggradation of the gravel.

In 1895 at Allenton (Bemrose & Deeley, 1896), in a layer of dark sand immediately above or forming the uppermost part of the Beeston gravels, the skeleton of a whole hippopotamus, together with the breast bone of *Elephas* and the femur of *Rhinoceros* (species not indicated), were found together with plant remains which indicated a temperate climate. The contained artifacts at Beeston include rolled mid-Acheulean hand-axes and Clactonoid flakes but fresh Levallois flakes. These two facts prompt a dating to the last interglacial (Catuvellaunian—Cornovian of Arkell; Second Welsh—Irish Sea ice of Wills; the Eemian of Woldstedt) since King (1955, 204) has suggested that an Eemian dating for hippopotamus yielding deposits and the evidence from the Thames and East Anglia is suggestive of a Last Interglacial date for the English Levallois. Remains of *Elephas antiquus* were found at Barrow-on-Soar (Plant, 1859, 174), probably of the same aggradation, which again suggests an interglacial date.

This would mean that the Beeston aggradation took place in the same interglacial as the deposition of the Hilton fluvio-glacial terraces, yet the evidence from Willington points to twenty feet of downcutting to the base of the Beeston Terrace, which would suggest a river eroding to a lower base level caused by the falling sea-level of a cold period. Mitchell & Stevenson (1955, 96) for the area near Rugeley have argued on morphological grounds that the terrace postdates the recent glacial marginal phenomena of the Irish Sea ice. At Brookend, three miles from Uttoxeter, Pocock (1929, 309–10) described how a small moraine projects into the valley and is older than the Second terrace. Clayton (1951) also independently observed how the terrace postdates the outwash gravels of the Irish Sea glacier in the Blithe Valley.

A further observation on the Beeston Terrace can be made. The anomalous Nottingham–Newark course of the Trent would seem to date from the retreat stage of the Eastern Glaciation when the release of large volumes of meltwater of the Northern ice combined with the ponded water of the melting blocks of Main Eastern ice to cut the new course. As interglacial conditions became established, aggradation could be expected to take place, of which the gravels at Bassingfield are a remnant. Yet the Bassingfield gravels are a correlate of the Beeston gravels, so that if the cutting of the Trent trench is placed in the retreat stage of the Eastern Glaciation and the later date be accepted for the Beeston gravels, then two sets of older gravels should be found in the Trent trench, yet only those at Bassingfield have been distinguished. The whole problem of the dating of the Beeston Terrace still remains open.

(c) The Flood-plain Terrace

The Beeston Terrace was downcut fifty feet at Bassingfield, forty-five feet at Willington, during an ensuing cold period, following which aggradation took place to form the Flood-plain Terrace. This Flood-plain, or No. 1 Terrace, is buried beneath the alluvium above Beeston and varies in thickness from twenty to thirty feet. Below Newark the existence of a buried channel has been indicated by Swinnerton (1937, 8), who has shown that the solid floor of the Flood-plain Terrace sinks from one foot above sea-level at Cromwell to thirty-five feet below sea-level in the next fourteen miles. Where recent borehole evidence around Carlton and Holme Pierrepont has enabled a cross-section of the valley floor to be drawn (see Fig. 8), the base of the Flood-plain Terrace is shown to be five to ten feet deeper to the north of Holme Pierrepont than it is to the south. Below Beeston the Trent is incised into the Flood-plain Terrace gravels, giving a low terrace seven to ten feet above the level of the alluvium. The presence of large flats belonging to this low terrace between Nottingham and Newark

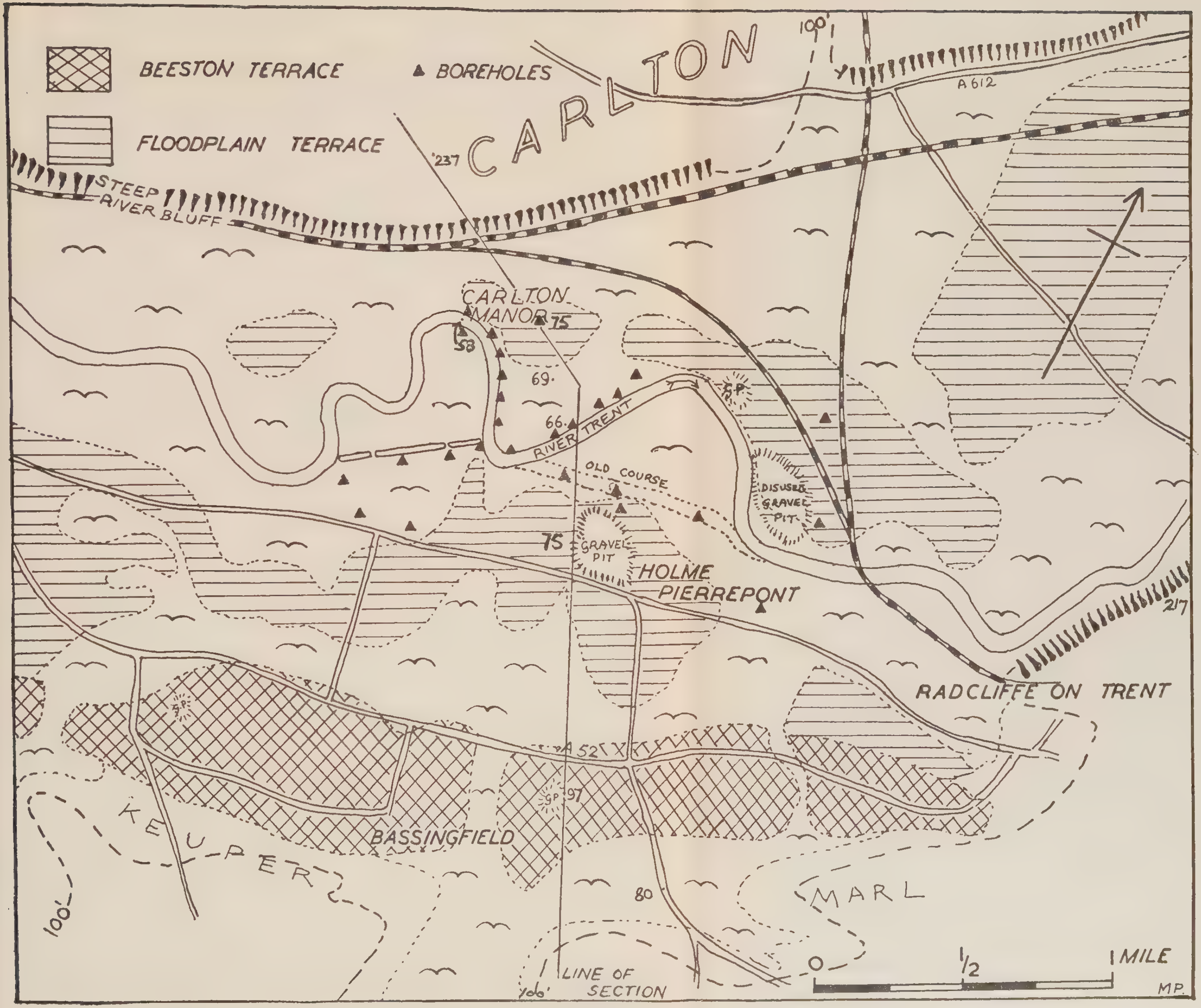

Fig. 6

[To face p. 302

show it to be of comparatively recent date. Clayton (1953, 202) has observed how there is a steepening in the long profile below Nottingham and presumes this incision to be a head of rejuvenation working back.

These morphological features suggest the following succession of events postdating the Beeston aggradation:

1 Downcutting to base of Flood-plain Terrace;
2 Aggradation of Flood-plain Terrace;
3 Cutting of deep channel below Newark;
4 Burial of channel and incision of Flood-plain gravels to form Low Terrace;
5 Deposition of gravels and modern alluvium.

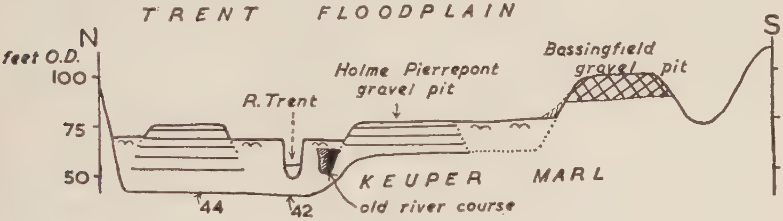

Fig. 7

Lithologically the Flood-plain gravels differ from those of the Hilton and Beeston gravels, particularly above Nottingham, in that the erratic content derived from the erosion of the Eastern Drift becomes negligible and pebbles derived from Derbyshire and the west are found. At Swarkeston (Appendix I), Derbyshire, rocks constitute more than 6% of the gravel compared to 2.4% for rocks derived from the Chalky boulder clay; at Hemington more than 11% are derived from the north and west, whilst Mitchell & Stevenson (1955, 98), from a gravel pit at Kings Bromley, found pebbles of Carboniferous Sandstone, Millstone Grit and Scottish and Lake District rocks. This suggests that the erosion of the deposits of the Irish Sea Glaciation contributed to the formation of the Flood-plain gravels. The gravel is worked 'wet' at the pits either by suction pumps or drag line below the watertable so that sections are seldom seen. At Swarkeston the lower levels of the gravel seemed to contain included lumps of clay, though it was impossible to say whether they represented boulder clay, whilst in the upper observed part of the section few stones were found above two inches in size, which gives some indication that the aggradation was of the more normal type of river aggradation.

Bones of *Bos primigenius*, *Bison priscus*, *Cervus dama*, *Rangifer tarandus*, *Elephas primigenius*, *Rhinoceros tichorhinus* have all been found in the gravels of the Flood-plain Terrace of the Trent and Soar (Appendix II) and indicate a last glacial date for the aggradation. Armstrong (1939, 41) reported quartzite implements similar to those from the Mousterian levels of Pin Hole, but has not published the material, so that it is impossible to confirm this.

5. THE NEWER DRIFTS, DRAINAGE CHANGES AND CORRELATIONS

The Newer Drifts did not affect the area. Mitchell & Stevenson (1955) have indicated that the Irish Sea ice, identified by a smaller amount of dissection than the Eastern Drifts and its glacial marginal phenomena, banked up against Cannock Chase, round whose north-east side a tongue of ice projected into the Trent Valley. The Newer Drifts of Lincolnshire still have to be intensely studied, though the succession described by Jukes-

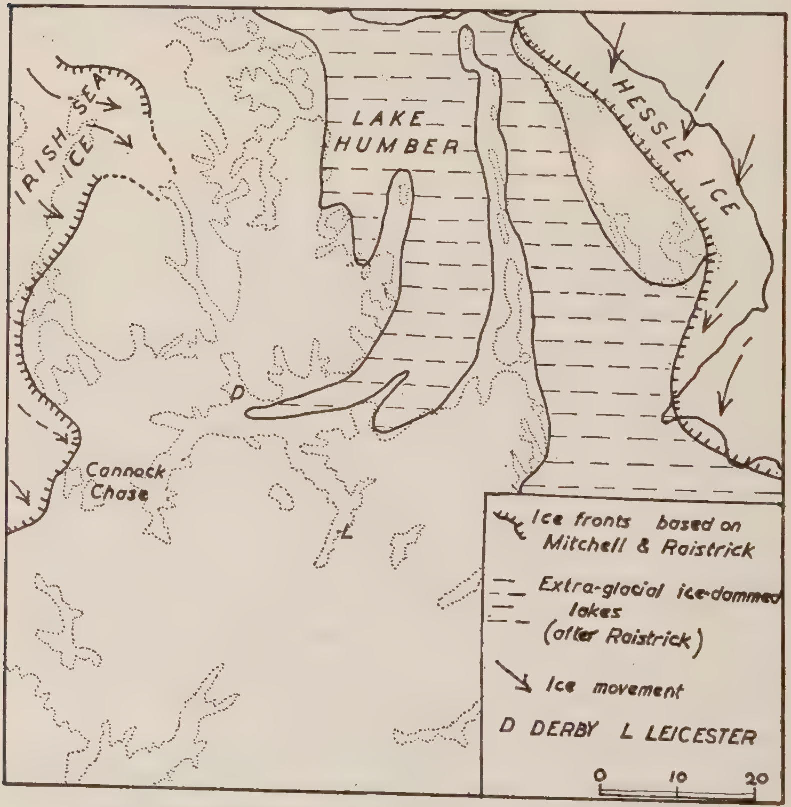
IRISH SEA ICE
LAKE HUMBER
HESSLE ICE
D
Cannock Chase
L
Ice fronts based on Mitchell & Raistrick
Extra-glacial ice-dammed lakes (after Raistrick)
Ice movement
D DERBY L LEICESTER
0
10
20

Fig. 8. Last Glaciation all stages. Contoured 200 feet and 600 feet

Browne (1879), and more recently by Swinnerton & Kent (1949), indicate two boulder clays belonging to the Newer Drift, the later of which is the Hessle, normally correlated with the Hunstanton of East Anglia. The Hessle, or Brown boulder clay (Swinnerton & Kent, 1949, 100), banked against the lower slopes of the Wolds up to about 100 feet. In Yorkshire a further glacial stage is indicated by the Flamborough moraine, whose independence of the Hessle is inferred by the new evidence of Farrington & Mitchell (1951). There is thus a possibility of three cold periods postdating the Eastern Glaciation, which would comprise the three main stadia of the Last Glaciation, a fourth stadia being represented from Scottish and palynological evidence.

During the Last Glaciation the Trent assumed its present-day course. The younger gravels north of Lincoln indicate a river course along the present line to the Humber and a course round the Eagle gravels to the Lincoln Gap. It is probable that left-bank tributaries of the Trent cutting down to a lower base level of a cold period developed an easier course for the Trent to the north across the Keuper Marl lowlands, whilst at the same time right-bank tributaries of the Humber eroded the present lower course of the Trent, so that in time by capture a new course would come into being. It is impossible to indicate when the present course came into being, though the buried channel below Newark suggests that it was in being at that time.

Much has been written about Lake Humber, a lake first suggested by Carvell Lewis in 1894 and elaborated by Kendall in 1902 and Raistrick in 1934 (Map 2, No. 4). The suggestion is that the Hessle ice by blocking the outlets for the Trent and south Yorkshire and Lincolnshire drainage areas caused a ponding-up of water to possibly 300 to 400 feet (Gayner & Melmore, 1936). The only outlet for the lake would be that of the Ouse–Waveney Gap (Kendall, 1902, 560), though Harmer (1907) had thought of the Ancaster and Lincoln gaps having their origin as overflow channels of the lake. Dalton (Dalton, 1941, 261) suggested that the Dove–Derwent gravels at 150 feet (the Hilton Terrace gravels) are beach and delta gravels of this lake. The Lincoln and Ancaster gaps and the Hilton gravels have however been shown to precede the accepted date for Lake Humber. Though a Lake Humber is feasible, no features suggesting its existence have been found in the Middle Trent basin, though the flooding of the Pin Hole Cave up to 250 feet O.D. (Armstrong, 1930) could represent the ponding of side streams flowing into the lake.

Shotton's work on the West Midlands and West's & Donner's on East Anglia and the East Midlands provide a correlation of the Eastern Glaciation with the Wolston Series and the Gipping, which makes the Pennine Drift the correlate of the Bubbenhall Clay and the Lowestoft boulder clay. The chronological position of the Beeston Terrace is rather in dispute due to the conflicting morphological and palaeontological evidence. The palaeontological evidence from Grotte des Enfants and Castille, which show a faunal survival of forest species into the second phase of the Last Glaciation and the pedological evidence of Romanelli (Blanc, 1920) suggest that the second phase of the Last Glaciation in southern Europe was the most severe. If this were so it would allow of the possibility of the survival of the hippopotamus, though the evidence of northern Europe (Woldstedt, 1950) and North America (Flint, 1947, 242) would suggest that the first phase was the most intense. The presence of hippopotamus from Terrace No. 3 of the Avon suggested to Shotton a correlation with the Beeston Terrace, whilst the 'conspicuously cold' fauna of Avon No. 2 would suggest correlation with the main aggradation of the Trent Flood-plain Terrace (Shotton, 1953, 236).

APPENDIX I

Gravel and Boulder Clay Analyses

Analyses were made of the gravel and boulder clay at fifteen localities to determine the lithological content. The method employed was that described by Krumbein & Pettijohn (*Manual of Sedimentary Petrography*, p. 44, New York), in which from eight to ten samples are taken at regular intervals along the section and mixed together and the composite sample quartered until a small enough sample is left for lithological analysis. The pebbles examined were all above 1 cm. in diameter.

Gravels

1. HILTON TERRACE

	Bunter Pebbles %	Flint (grey) %	Carbonif. lmst. sandst. black chert %	Others %	No. of Pebbles
Willington N. pit	82½	7½	6	4	245
Willington S. pit	90	5½	3	1½	339
Hilton E. pit	72½	13½	?	14	100

Samples were very difficult to take at Hilton due to filling up of pits with rubbish and water. Large boulder clay erratics with tiny chalk nuggets were found at Hilton. From gravel dumps a count was made of flint type, the proportion of black to grey being 3 to 25. At Willington samples were taken in the lower halves of the sections.

2. BEESTON TERRACE

Due to lack of gravel workings in this aggradation above Beeston, no samples were obtainable near to where the Hilton gravels had been collected.

	Bunter Pebbles	Flint	Jurassic erratics	Carboniferous erratics	Others	No. of Pebbles
	%	%	%	%	%	
Beeston, Stoney Street	82	7½	½	1½	8½	339
Bassingfield	76½	3½	2	2	6	273

3. FLOOD-PLAIN

(a) Below Beeston

	Bunter Pebbles	Flint	Carbonif. and Derbs. erratics	Jurassic erratics	Others	No. of Pebbles
	%	%	%	%	%	
Holme Pierrepont	82	13	2	—	3	347
(b) Soar Valley						
Quorn	35	30	—	20½	14½	224
Syston	27	24 (grey) ½ (black)	—	37	12 (chalk 1½)	249

(c) Above Beeston

	Bunter Pebbles	Flint	Carbonif. and Derbs. erratics	Jurassic erratics	Others	No. of Pebbles
	%	%	%	%	%	
Stretton	86	1½	8	–	4½	337
Swarkeston	90	2	6	?	2	214
Hemington	76½	4	11	?	8½	375
(d) Below Newark						
Snow Sewer (Trent River Board sample)	72	10½	3½	?	14	141

4. GLACIAL

Tilton (Leic.)	12	12½	—	61	14½	213

5. BOULDER CLAY

	Chalk %	Flint %	Jurassic erratics %	Triassic erratics %	Not identified %
Chellaston Chalky b.c. (Main Eastern)	35	17	9	26	13
Kilby Bridge b. Chalky b.c. (Main Eastern)	55	4	23	8	10
a. Charnwood Drift (Pennine Drift)	—	—	—	88	others incl. Charnwood rocks 12

APPENDIX II

Faunal Remains from the River Gravels

No attempt has been made to gather together the records of the finds of Pleistocene mammalian remains from the gravels of the Trent and its tributaries. Montague Brown in his *Vertebrate Animals of Leicestershire and Rutland* (London, 1889) gave details of the bulk of these found in Leicestershire and housed in Leicester Museum, whilst Leith Adams in his monograph on *Fossil Elephants* (Palaeontological Society, 1877–81) mentioned that three molars (two of *Elephas primigenius* and one of *E. antiquus*) was all he could then record from the area. Unfortunately, the small number of observers and the rapid mechanisation of the gravel pits has meant that only the more spectacular mammoth molars and tusks are brought to scientific notice.

1. HILTON TERRACE

Bos primigenius, tibia   Willington N. pit   Univ. Museum, Nottingham.

The provenance of this specimen is suspect and was recovered from the gravel dump.

2. BEESTON TERRACE

Hippopotamus, femur of *Rhinoceros* and breast bone of *Elephas* (species not stated) Allenton. (Bemrose & Deeley, 1896, 497–500) Hippopotamus in Derby Museum.

Elephas antiquus, tusks, four teeth, part of femur and large fragment of scapula. Barrow-on-Soar. (Plant, 1959, 74. *Trans. Leicester lit. phil. Soc.*, 1958, 20–1). Leicester Museum.

3. FLOOD-PLAIN TERRACE

Numerous finds of mammalian remains have come from these gravels. Material comprising mammoth *Elephas primigenius* molars, portions of tusks and a scapula from Attenborough and Hazelford are housed in the Palaeontology Museum of the University of Nottingham; at the Newark Museum mammoth tusks and molars have come from Girton (Oak Doors gravel pit), Balderton, Besthorpe and Staythorpe; at Leicester Museum mammoth remains have come from gravel workings along the Soar at Belgrave, Leicester, Thurmaston, Humberstone, Loughborough and Kegworth; teeth and bones of *Rhinoceros tichorhinus* from Belgrave, Leicester, Thurmaston and a whole jaw from Sileby; skull fragments of *Bison priscus* from Abbey Meadow, Leicester and Kegworth; *Rangifer tarandus* from Leicester, Aylestone and Belgrave; *Cervus elephas* from Braunstone Gate, Leicester, Mountsorrel and Barrow-on-Soar; *Cervus dama* from various Leicester pits; *Equus caballus* from Belgrave and Leicester and remains of *Bos primigenius* from Belgrave, Leicester, West Langton and Helpstone; at the British Museum (N.H.) mammoth remains from Syston.

Numerous other bones, particularly of *Elephas primigenius*, have been found at scattered localities and are in private hands.

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REFERENCES

ARKELL, W. J. 1947. *The Geology of Oxford.* Oxford.

ARMSTRONG, A. L. 1930. Excavations in the Pin Hole Cave, Cresswell. *Proc. prehist. Soc. E. Angl.*, **6**, No. 25.

———. 1939. Palaeolithic Man in the North Midlands. *Mem. Manchr. lit. phil. Soc.*, **83**, 87.

BADEN-POWELL, D. F. W. 1948. The Chalky Boulder Clays of Norfolk and Suffolk. *Geol. Mag.*, **85**, 279–96.

BLAKE, J. F. 1906. *Victoria County History of Nottinghamshire*, **1**, 32.

BLANC, G. A. 1920. Grotta Romanelli. *Archive per l'Anthropologia, e la Etnologia*, **50**, 65–103.

BEMBROSE, ARNOLD H. H. & R. M. DEELEY. 1896. Discovery of Mammalian Remains in the Old River Gravels of the Derwent near Derby. *Quart. J. geol. Soc. Lond.*, **52**, 497–510.

BRIGGS, J. J. 1873. *The History and Antiquities of Hemington.* London.

CARRUTHERS, R. G. 1953. *Glacial Drifts and the Undermelt Theory.* Newcastle upon Tyne.

CLAYTON, K. M. 1951. *Thesis—Denudation Chronology of the Middle Trent Basin.* Sheffield University.

———. 1953. Glacial Chronology of the Middle Trent Basin. *Proc. Geol. Ass., Lond.*, **64**, 198.

DALTON, A. C. 1941. Lake Humber. *Northw. Nat.*, Dec., p. 256.

DEELEY, R. M. 1886. The Pleistocene Succession in the Trent Basin. *Quart. J. geol. Soc. Lond.*, **42**, 437–80.

DUIGAN, S. L. 1956. Interglacial Plant Remains from Wolvercote Channel, Oxford, and Pollen Analysis of the Nechells Interglacial Deposits, Birmingham. *Quart. J. geol. Soc. Lond.*, **112**, 363–91.

FARRINGTON, A. & G. F. MITCHELL. 1951. The End-Moraine North of Flamborough Head. *Proc. Geol. Ass., Lond.*, **62**, 100–6.

FLETCHER, G. 1891. Traces of the Great Ice Age in Derbyshire. *J. Derbysh. archaeol. nat. Hist. Soc.*

FLINT, R. F. 1947. *Glacial Geology and the Pleistocene Epoch.* New York.

FOX-STRANGWAYS, C. 1900. The Geology of the Country between Atherstone and Charnwood Forest. *Mem. geol. Surv. U.K.*

———. 1903. The Geology of the Country near Leicester. *Mem. geol. Surv. U.K.*

———. 1905. Geology of the Country between Derby, Burton-on-Trent, Ashby-de-la-Zouch, and Loughborough. *Mem. geol. Surv. U.K.*

———. 1907. Geology of the Leicestershire and Derbyshire Coalfield. *Mem. geol. Surv. U.K.*

GAYNER, J. S. & S. MELMORE. 1936. The Pleistocene Geology of the area between the Tees and the Trent. *Quart. J. geol. Soc. Lond.*, **90**, 362–4.

HARMER, F. W. 1907. On the Origin of Certain Canon-like Valleys associated with Lake-like Areas of Depression. *Quart. J. geol. Soc. Lond.*, **63**, 486–90.

———. 1928. The Distribution of Erratics and Drifts. *Proc. Yorks. geol. (polyt.) Soc.*, **21**, 79–150.

HOLLINGWORTH, S. E. & J. H. TAYLOR. 1946. An Outline of the Geology of the Kettering District. *Proc. Geol. Ass., Lond.*, **62**, 204.

HULL, E. 1860. Geology of the Leicestershire Coalfield. *Mem. geol. Surv. U.K.*

IRVING, 1876. The Geology of the Nottingham Region. *Proc. Geol. Ass., Lond.*

JOWETT, A. & J. K. CHARLESWORTH. 1929. The Glacial Geology of the Derbyshire Dome and the Western Slopes of the Southern Pennines. *Quart. J. geol. Soc. Lond.*, **85**, 307–37.

JUKES-BROWNE, A. J. 1879. The Hessle Boulder Clay in Lincolnshire. *Quart. J. geol. Soc. Lond.*, **35**, 397.

———. 1883. On the Relative Age of Certain River Valleys. *Quart. J. geol. Soc. Lond.*, **39**, 596–610.

———. 1885. The Boulder Clays of Lincolnshire. *Quart. J. geol. Soc. Lond.*, **41**, 114–32.

———. 1885. The Geology of South-West Lincolnshire. *Mem. geol. Surv. U.K.*

KENDALL, P. F. 1902. A System of Glacier Lakes in the Cleveland Hills. *Quart. J. geol. Soc. Lond.*, **58**, 471–569.

KING, W. B. R. 1950. Some Periglacial Problems. *Proc. Yorks. geol. (polyt.) Soc.*, **28**, 43–50.

———. 1955. The Pleistocene Epoch in England. *Quart. J. geol. Soc. Lond.*, **111**, 187–208.

LAMPLUGH, G. W. & W. B. WRIGHT. 1908. The Geology of the Country between Newark and Nottingham. *Mem. geol. Surv. U.K.*

LINTON, D. L. 1951. Midland Drainage. *Advanc. Sci., Lond.*, **7**, 449–56.

MARR, J. E. 1926. The Pleistocene Deposits of the Lower Part of the Great Ouse Basin. *Quart. J. geol. Soc. Lond.*, **82**, 82.

MITCHELL, G. H. & I. P. STEVENSON, 1955. Geology of the Country between Burton-on-Trent, Rugeley and Uttoxeter. *Mem. geol. Surv. U.K.*

MOLYNEUX, W. 1869. *Burton-on-Trent; its History, its Waters and its Breweries.* London.

MORTON, J. 1712. *Natural History of Northamptonshire*. London.

NICHOLS, J. 1795–1815. *History of Leicestershire*. London.

PENNING, W. H. & Others. 1886. *Geological Map*. Sheet 83.

PLANT, J. 1859. Notice of the Occurrence of Mammalian Remains in the Valley of the Soar. *The Geologist*, **2,** 74.

POCOCK, T. I. 1929. The Trent Valley in the Glacial Period. *Z. Gletscherk. Glazialgeol.*, **17,** 302–18.

————. 1954. The Rivers Witham and Devon in the Glacial Period. *Z. Gletscherk. Glazialgeol.*, **3** (1), 47–54.

POTTER, T. R. 1842. *Charnwood Forest*. (With Appendix on Geology by J. B. Jukes.) London.

RAISTRICK, A. 1934. The Correlation of Glacial Retreat Stages across the Pennines. *Proc. Yorks. geol. (polyt.) Soc.*, **22,** 3.

RAMSEY, A. C. 1863. *The Physical Geography and Geology of Great Britain.*

SABINE, P. A. 1949. The Source of some Erratics from North-East Northamptonshire and Adjacent Parts of Huntingdonshire. *Geol. Mag.*, **86,** 255–60.

SHIPMAN, J. 1879. The Alluvial and Drift Deposits of the Trent Valley near Nottingham. *Notts. Naturalists' Soc.*

————. 1883. The Alluvial and Drift Deposits of the Leen Valley. *Midl. Nat.*

SHOTTON, F. W. 1953. The Pleistocene Deposits of the Area between Coventry, Rugby and Leamington and their Bearing upon the Topographical Development of the Midlands. *Phil. Trans.* B, **237,** 209–60

SWINNERTON, H. H. 1937. The Problem of the Lincoln Gap. *Trans. Lincs. Nat. Un.*

————. 1948. *Guide to the Geology of the East Midlands. Pleistocene and Later Deposits.* Nottingham University.

———— & P. E. KENT. 1949. The Geology of Lincolnshire. *Trans. Lincs. Nat. Un.*

TOMLINSON, M. E. 1935. The Superficial Deposits of the Country North of Stratford-on-Avon. *Quart. J. geol. Soc. Lond.*, **91,** 423.

VAN DER VLERK, I. M. 1953. The Stratigraphy of the Pleistocene of the Netherlands. *Proc. Acad. Sci. Amst.* B, **1,** 34–44.

WEST, R. G. 1954. The Hoxne Interglacial Reconsidered. *Nature, Lond.*, **173,** 187.

———— & C. B. M. MCBURNEY. 1954. The Quaternary Deposits at Hoxne, Suffolk, and their Archaeology. *P.P.S.*, **20,** 131–55.

———— & J. J. DONNER. 1956. The Glaciations of East Anglia and the East Midlands. *Proc. G.S.*, 79–80.

WILLS, L. J. 1950. *The Palaeography of the Midlands*. 2nd ed. Liverpool.

WOLDSTEDT, P. 1950. *Nord deutschland und angrenzende gebiete im Eiszeitalter*. Stuttgart.

ZEUNER, F. E. 1945. *The Pleistocene Period.* London.

A Spring Pit with Mound Structures

by IAIN A. WILLIAMSON

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ABSTRACT: A circular depression containing conelets in littoral muds is described. The conelets are considered to be formed by emergent springs developed at a hydrostatic low in the base of the depression; the origin of the low is uncertain. Crescentic mounds may be useful in the determination of the direction of the water stream flowing from similar features, should they be found in the geological column.

ON THE twenty-second of September 1957, during low tide, the writer noticed the sedimentation phenomena, described below, on the foreshore at Grange-over-Sands, Lancashire. This foreshore, composed of a sticky brown mud, lies south of the estuary of the River Gilpin. The features lay fifty yards seaward (404768) of High Water Mark, between it and the Kent Channel. The latter is one of two river channels which at low tide flow across the north-eastern arm of Morecambe Bay. At the time of observation the tide was at about its ebb and thus the maximum area of foreshore was exposed, that is, the whole of this arm of Morecambe Bay.

The saucer-like depression was about four inches deep and some three feet in diameter. The depression was partially filled with water to a depth of about one inch and drained seawards by a small channel which extended for several feet (Fig. 1).

The floor of the depression, relatively flat and composed of compact sediment, was occupied by four small mounds or conelets, each from one to three inches in diameter and about half an inch in height. From small craters at the apices of two of the mounds flowed springs of water; from both springs the water fountained out causing slight turbulence on the surface of the water in the depression; the water contained a fine suspension of clay floccules and in one instance a small 'worm'. This sediment in suspension was deposited on the slopes of the mounds in a loose aggregate. That the mounds were formed by the deposition of the sediment carried by the springs was particularly obvious in two examples (one still in process of active formation) where crescentic ramparts were built up around the orifices of the springs. The concave sides of the crescents lay on the opposite side to the channel draining the depression. The shape of the crescents is the result of a slight seaward drift of the floccules erupted by the springs. All the mounds were just below water-level and were developed after the retreat of the tide. Certainly the channel draining the depression was formed then, for such a feature would not develop when the surrounding area was submerged; the small mounds would also be destroyed by the backwash of the tide as they consisted of very loosely packed sediment.

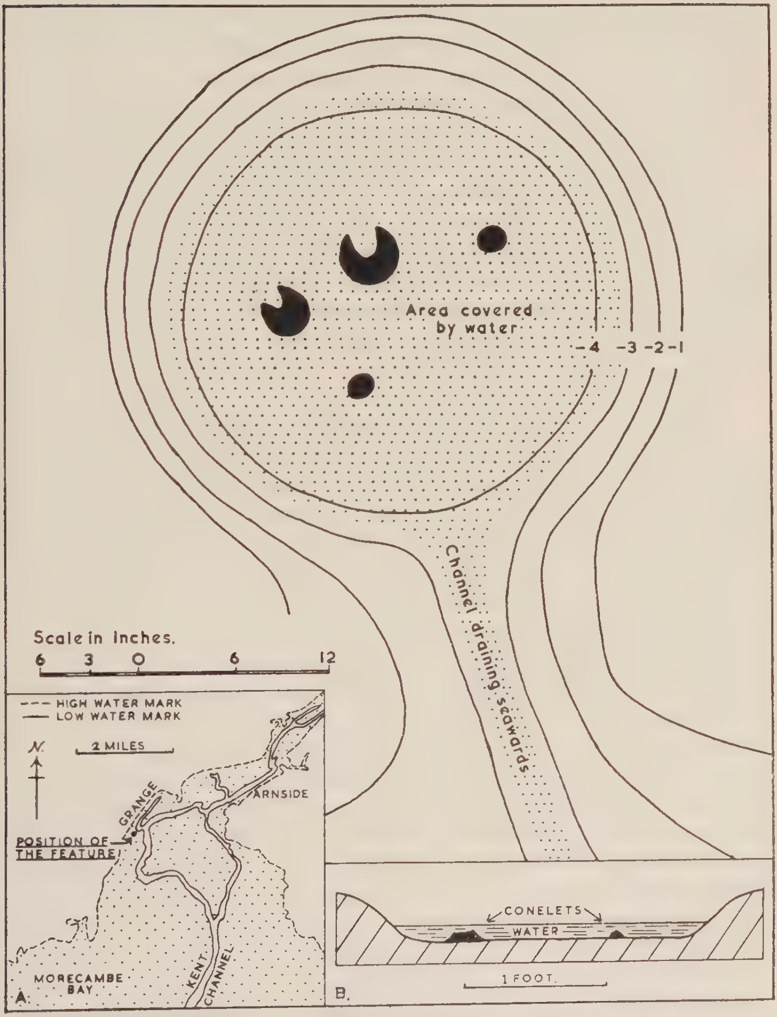

Fig. 1. Diagrammatic plan of the features. The 'contours' shown are merely form lines at approximately one inch intervals below the general surface of the foreshore. The conelets are coloured black.

Inset A. Sketch-map showing the geographical position of the feature.

Inset B. Diagrammatic section across the depression and conelets.

The form, origin, and extremely localised occurrence of the whole feature (for no other similar phenomena were seen in the whole area between Kents Bank and Grange-over-Sands) is difficult to explain. The sediments along this part of the foreshore were clearly saturated with water, this being particularly obvious in walking across it, when one repeatedly sank up to and even over the ankles. Expulsion of pore-water by compaction may have caused the formation of the conelets; a relationship certainly existed between the expulsion of water from the conelets and compaction of the sediments, for it was seen that when standing close to the crater the springs appeared to be more powerful than when one stood farther away. However, the conelets were more probably formed by the development at the base of the depression of a local hydrostatic head, sufficiently large to allow the conelet-springs to form, but small enough to restrict their occurrence to the base of the depression.

The depression bears some resemblance to certain previously described structures:

(a) Spring pits. Quirke (1930) described craters or bowl-shaped depressions less than two feet in diameter formed on a sandy lacustrine beach during flooding. They were produced by ascending waters and were characterised by the concentration of coarser sediment in the centre and the finer around the periphery, which is raised above the level of the surrounding sand. The pits formed both above and below water, in the former case being characterised by a small drainage channel leading from the bottom of the pit towards the lake margin.

(b) Pit and mound structures. Kindle (1916) described shallow pits resembling rain-drop impressions which had been produced experimentally in clay suspensions. In a saline solution containing mud particles, currents formed and moved upwards through the rapidly settling muds, which, as soon as the currents ceased, closed inwards around the vertical channels formed by the currents and produced a small pit upon the surface of the sediment. These experimentally produced features were of much smaller size than the present depressions, though Kindle records certain depressions in the Bay of Fundy up to twelve inches in diameter and four inches deep which he considered could have been formed in the way described.

(c) Gas pits. Maxson (1940) described how the generation of methane by the decomposition of organic debris in submerged mud in the headwaters of Lake Mead, U.S.A., resulted in the formation of crater-like pits up to six feet in diameter and with a depth of four feet. The considerable size of the features was a result of erosive action in the vacinity of rising gas bubbles.

The Grange-over-Sands depression bears the closest resemblance in shape and size to the spring pits described by Quirke, though the outward grading of sediment from coarse to fine is absent. The cause of the hydrostatic head sufficient for the formation of the solitary spring pit is difficult to envisage. The origin of pit and mound structures is such that they will probably form in groups and not singly. The depression may have originated as a gas pit, though its shallow depth is in contrast with the depths recorded by Maxson, and this theory of formation is unlikely.

The exact mode of formation of the depression is not known with certainty, but the conelets are considered to have been formed after the retreat of the tide from the area, probably by the development of a local hydrostatic head at the base of the depression due to an unknown cause.

A search of the literature has failed to reveal any descriptions of structures similar to the depression with its crescentic mounds. Should the crescentic structures be found in the geological column, they would be useful indicators of the direction of the water stream flowing from the depression at the time of formation and would provide valuable environmental information.

REFERENCES

KINDLE, E. M. 1916. Small Pit and Mound Structures developed during Sedimentation. *Geol. Mag.*, **3,** 542–7.

MAXSON, J. H. 1940. Gas Pits in Non-Marine Sediments. *J. sediment. Petrol.*, **10,** 142–5.

QUIRKE, T. T. 1930. Spring Pits; Sedimentation Phenomena. *J. Geol.*, **38,** 88–91.

Aspects of the Lithology of the Wessex Upper Greensand

by GEOFFREY R. TRESISE

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ABSTRACT: The lithological variations shown by the Upper Greensand within the Wessex area are first considered. Glauconite, phosphate, limestone and chert, all of which characterise the series, are then discussed in turn. Five distinct types of glauconite occur, often in different sedimentary associations; the mineral has formed from a variety of source materials, but in all cases seems to have solidified from an original gelatinous state. Phosphatic nodules may form by replacement of calcareous shells, sponges or limestone concretions, and are particularly associated with depositional breaks and richly glauconitic horizons. Calcareous stone is mostly rich in detrital grains, being produced by the cementation by calcite of the surrounding sand. Nodules of pure limestone at certain horizons are thought to result from the recrystallisation of calcareous patches in the original sediment. The Upper Greensand cherts appear to have formed in fairly shallow but tranquil waters. A mass of silica gel, precipitated on the sea-floor, solidified into a nodule of porous stone which was subsequently converted into true chert by deposition of silica from solution. The arenaceous sediment was brought into the sea from a land-mass to the west.

1. INTRODUCTION

THE LITHOLOGICAL UNIT of the Upper Greensand comprises a dominantly arenaceous facies of Upper Albian age, best developed in southern England. It reaches its maximum thickness (about 180 feet) in Devon where it is the sole representative of the Albian. To the east the sands pass down into the dark-coloured Gault Clays which increase in thickness at the expense of the overlying arenaceous division until in Kent only the Gault is present. The total extent of the Upper Greensand in the area covered by the present study is shown on the accompanying map (Fig. 1).

The Upper Greensand consists of a series of sands which contain four components of particular interest—glauconite, chert, limestone and

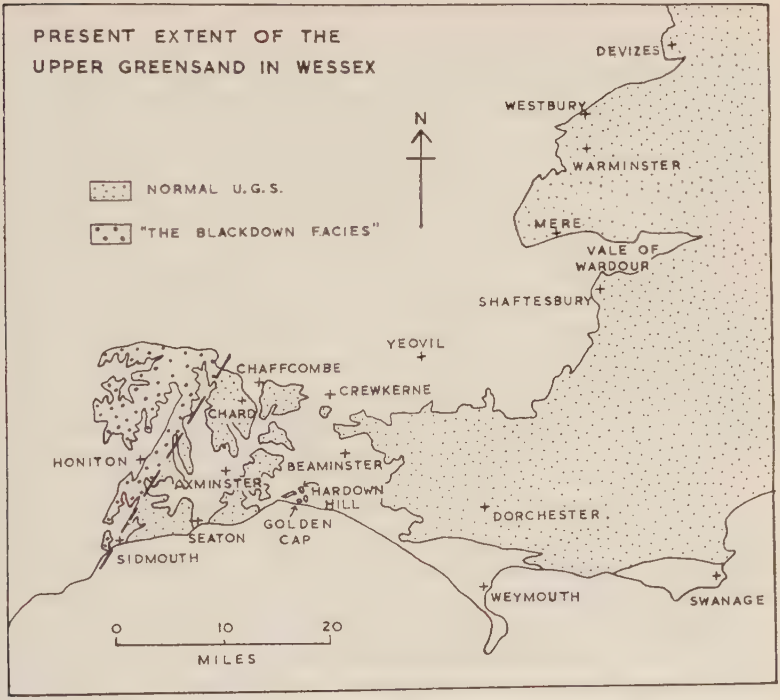


Fig. 1. Areal extent of the Upper Greensand (exposed or concealed by later sediments) in Wessex

phosphatic nodules. Since these are not always present in marine sediments, they may be assumed to form only under specifically favourable conditions, either on the sea-bed or within the accumulated sediment. Though each of these four constituents occurs in sediments of widely varying age, for them all to be present in the same series of beds is a much rarer phenomenon. All four occur in the British Portlandian, but in different areas or at different horizons. On the Dorset coast, the Portland Sands are glauconitic but chert occurs only in the overlying Portland Limestone, while near Swindon, where the beds tend to be glauconitic throughout, chert is absent. Only the Lower Greensand beds of Aptian age contain a similar assemblage and even here the resemblance is not complete. In the Hythe Beds of the more westerly parts of the Weald, cherts are found in sands which are glauconitic, though not so richly so as to be true ‘green-sands’. Calcareous nodules are generally rare and those which do occur are not pure limestone, but are cemented partly by calcite and partly by silica (Hayward, 1932). The Folkestone Sands of east Kent are glauconitic, but are typically free from both chert and limestone. The closest resemblance to the Upper Greensand is shown by the Bargate Beds of Surrey, where both chert and limestone occur in a glauconitic sand which locally contains phosphatic material, mostly replacing fossils derived from the Jurassic sediments. Richardson (1947) has, however, shown that the cherts are not original features of the Bargate Beds, but have been formed by the epigenetic replacement of limestone—an explanation which, as will be shown, does not apply to the Albian types. Thus the glauconite–phosphate–chert–limestone assemblage of the Upper Greensand, if not completely unique among British sediments, is certainly very uncommon.

Pre-eminent among the previous accounts of these beds is the classic study of Jukes-Browne (1900). Perhaps the most important single aspect of this work was his clear demonstration that the earlier workers were mistaken in regarding the Upper Greensand as a formation wholly younger than the Gault. He showed that there was a lateral gradation of Gault Clay into the arenaceous sediments to the west and concluded that the two must be regarded as largely synchronous deposits formed in different parts of a single marine basin. Later Spath (1926) was to show that the Upper Greensand, unlike the Gault, was wholly of Upper Albian age and that the Lower Albian divisions present in south-east England are not represented in the west. No general account of the Upper Greensand has been published since 1900 although various authors have described local successions, among them Jukes-Browne & Scanes (1901) and Edmunds (1938) on the Mere district of Wiltshire, Arkell with Wright (1947) on the Dorset coast from Weymouth to Swanage, Smart (1955) on the Alton Pancras area of north Dorset, and Wilson, Welch, Robbie & Green (1958) on the Bridport and Yeovil district.

In Jukes-Browne's excellent stratigraphical account the Upper Greensand exposures were described in considerable detail. His work was, however, essentially descriptive and, though general conclusions were drawn as to the conditions prevailing in the Albian Sea, little attempt was made to explain the lithological variations of the sediment. Thus though glauconite was classed as a secondary mineral formed on the sea-bed, no indication was given of either the source material or the conditions under which the conversion took place. In the case of cherts, Hinde's identification of the nodules as 'sponge-rocks' was accepted without question, and their sporadic occurrence dismissed by analogy with the patchy distribution of sponge-fields on the present sea-bed.

A wide field thus remained open for research on these beds. The present work has been aimed mainly at the elucidation of the hitherto neglected petrological aspects, but inevitably entailed an initial study of Upper Greensand stratigraphy as revealed by present-day exposures. The general successions will be briefly summarised, prior to a more detailed consideration of the lithological features of the sediments.

2. THE DEVON COAST

The cliffs of the Sidmouth–Seaton district (Fig. 2) provide excellent exposures of Upper Greensand. Comparative columnar sections (Fig. 3) have been drawn for the beds seen at Dunscombe Cliff (30/148876), at Little Beach (30/224879) and, near Seaton, at the western end of Haven Cliff (30/257897), where the succession is more readily accessible than in the well-known section at White Cliff (30/235896), a mile or so to the west. At Dunscombe the top fifty feet of beds are well-exposed, but below this the succession shown is based on that of Jukes-Browne (1900). The series is broadly subdivided into the Foxmould Sands, glauconitic and with courses of calcareous stone, and the overlying Chert Beds. While the latter division is well exposed in the cliffs, exposures in the soft Foxmould Sands are discontinuous and estimation of their thickness is therefore difficult, though Jukes-Browne stated it to be eighty-five feet at White Cliff. Gault Clay is not developed in this western region, and the Upper Greensand rests directly on the underlying Triassic beds.

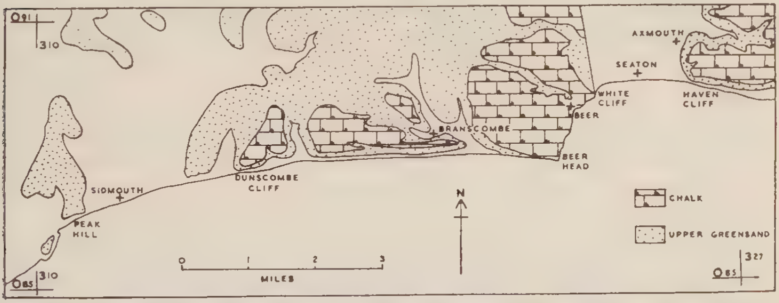


Fig. 2. Outcrops of the Upper Greensand and Chalk on the coast of south-east Devon

Comparing the columnar sections, one immediate point of interest is the thinning of the Chert Beds to sixty-seven feet at Little Beach, as against seventy-nine feet at Dunscombe and ninety-four feet near Seaton. Two explanations are possible: (a) deposition was more restricted at Little Beach than either to the east or to the west; (b) erosion subsequently removed part of the Little Beach succession. There is good reason to believe that the second is the correct explanation. The section shown was located some 150 yards west of Beer Head (30/227879), almost exactly on the line of the small-scale periclinal axis described by Smith (1957). He claimed that the erosion resulting from intermittent uplift along this axis explained the marked fluctuations in thickness seen in the Cenomanian along this coast. It is quite possible that erosion of the highest Albian sediments accompanied the initiation of this uplift at the beginning of the Cenomanian period. Such erosion would account for the sudden disap-

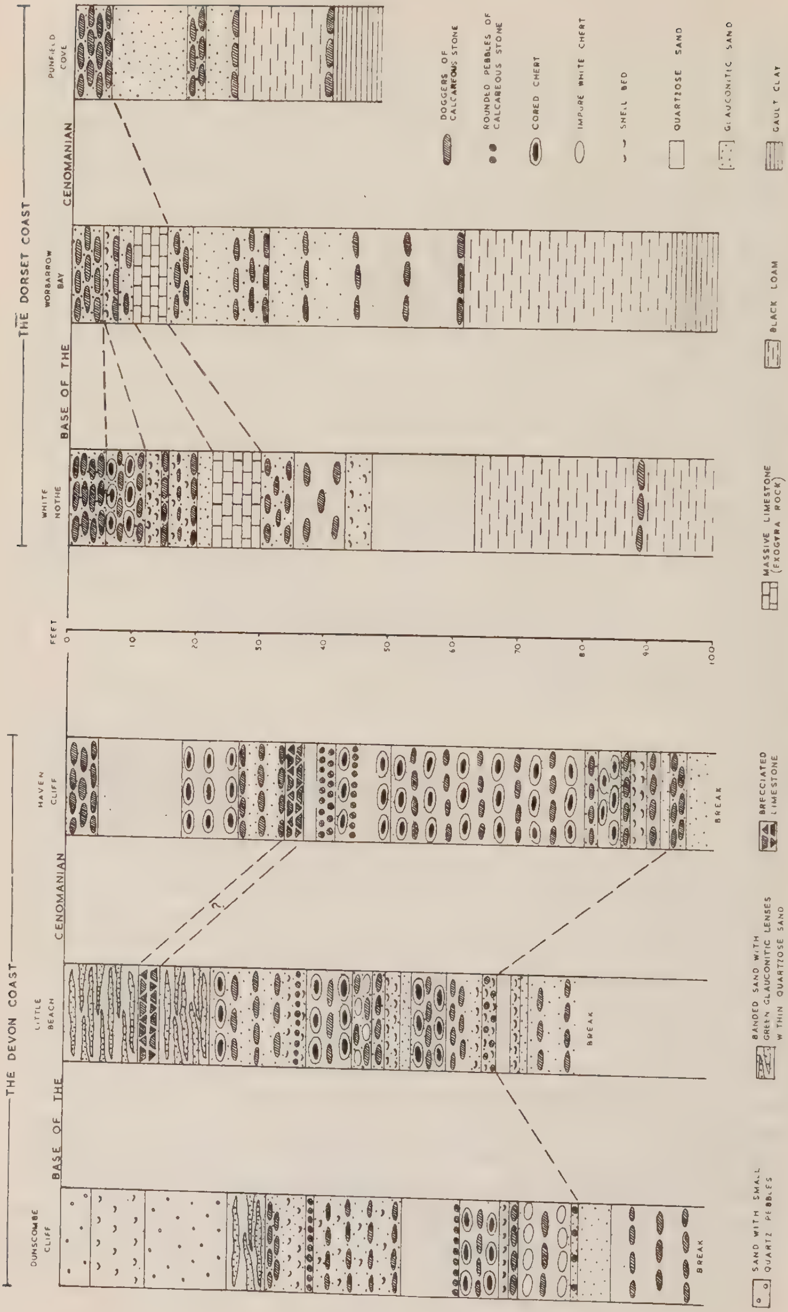


Fig. 3. Columnar sections showing Upper Greensand successions of the Devon and Dorset coasts

pearance of the concretion bed which forms the topmost horizon of the Upper Greensand at Haven Cliff, White Cliff and Beer Harbour.

Interesting light is thrown on this problem by the presence in the Haven Cliff section of a 'brecciated bed' in which angular blocks of laminated calcareous sandstone along the bedding planes alternate with thin seams of unconsolidated glauconitic sand. The brecciated bed appears to result from the shattering of such hard sandstone bands to give irregular blocks, around which the overlying sands then percolated. Only one such breccia occurs in the Upper Greensand succession, there being here no sign of the sandstone blocks being subjected to the rolling and abrasion which gave rise to the perfectly rounded components of the more common pebble beds. An identical bed occurs at the same horizon at White Cliff, and a three-foot breccia is also found at Little Beach. Here, however, it occurs only twelve feet below the base of the Chalk as against thirty-four feet near Seaton. The author would suggest that this apparent difference in horizon is due to the absence (as a result of erosion) of the highest twenty feet of Upper Greensand at Little Beach, and that the two are in fact contemporaneous. It is possible that the brecciation resulted from the first stirrings of the tectonic activity which persisted in this region throughout the Cenomanian.

Allowing for the fact that the Little Beach succession is probably incomplete, the sections show that the lower part of the Upper Greensand is of uniform nature along this coast, while the higher beds are more variable. The Foxmould Sands are rather more glauconitic to the east, and are green in colour near Seaton, grey or buff near Sidmouth. Glauconite rich sands characterise the basal foot or so of the Chert Beds but above this the sediments tend to be more sparsely glauconitic. Chert formation appears to have been first initiated in the west, since white siliceous stone occurs one foot above the Foxmould at Dunscombe, whereas Haven Cliff shows seven feet of chert-free beds. Chert is most extensively developed in the east, however, and near Seaton the main chert-bearing horizon is thirty-five feet thick. Chert is more sporadically distributed in the overlying beds which contain rounded pebbles, current-bedding and other evidence of disturbed waters. At Dunscombe sixty feet of chert-free beds underlie the Chalk and the highest twenty-five feet consist of coarse sands, rich in shell fragments and quartz gravel up to 5 mm. in diameter. Strong currents are indicated and the implication seems to be a general shallowing of the sea in late Albian times which was particularly marked in the west.

The sediments which occur at Peak Hill (30/109867) west of Sidmouth, differ in being completely non-calcareous. They are poorly graded glauconitic and limonitic sands containing occasional bands of brown chert. The general features are those of the region to the north—the 'Blackdown Facies' (see p. 326). The cliff here, unlike those to the east, has no capping of Chalk. Non-calcareous beds also occur in west Dorset—

Chert Beds being exposed on Hardown Hill (30/402944) while sixty feet of the underlying sands, free from both chert and calcareous stone, are seen on Golden Cap (30/406920) to the south. These fine-grained buff-coloured sands are equivalent to the Devon Foxmould, but are considerably less glauconitic. Again there is no capping of Chalk on these outliers.

3. THE DORSET COAST

The Weymouth–Swanage coast is illustrated by Fig. 4, and columnar sections from three localities are included in Fig. 3. The Upper Greensand overlies the dark clays of the Gault but, as this junction is everywhere concealed by cliff-falls, the thickness of the arenaceous beds cannot now be measured. The junction, as determined by previous workers, has however been included in two of the sections to illustrate the westward thickening of the Upper Greensand. In the case of the section at Punfield Cove (40/045813) near Swanage, the thickness shown is that given by Arkell & Wright (1947), while for Worbarrow Bay (30/866804) the figure of Jukes-Browne (1900) is utilised.

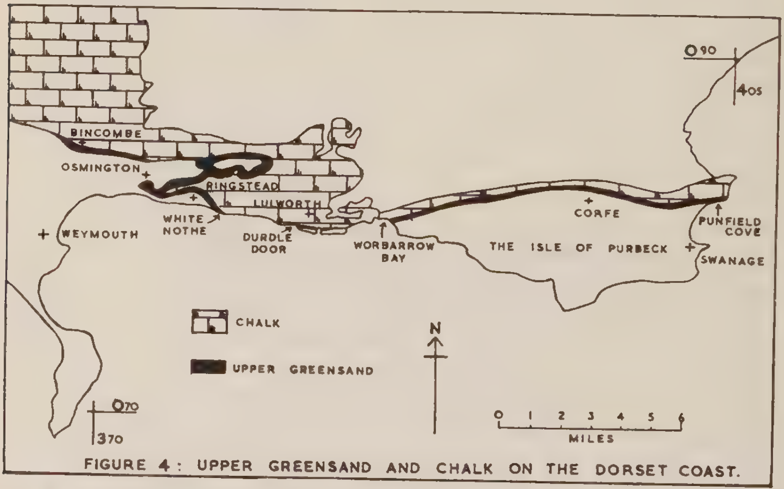


Fig. 4. Outcrops of the Upper Greensand and Chalk on the coast of central Dorset

The sections illustrate the lithological changes seen along this coast. Compared with the Devon coast sections, the following are the main points of interest:

(1) The eastward thinning of the Upper Greensand series and the corresponding thickening of the underlying Gault Clays. In Dorset a transitional series of black loams separates the two. At Punfield Cove

these loams contain pyrite nodules and, when treated with dilute hydrochloric acid, emit a strong smell of H_2S. They thus appear to have formed under anaerobic conditions.

(2) Though the thinning of the Upper Greensand may be partly explained by its lateral passage into Gault clays, the higher beds in particular are more condensed to the east. Thus the Exogyra Rock, which at White Nothe (30/770811) consists of eight feet of limestone occurring twenty-two feet below the Chalk, is represented at Punfield Cove by two feet of shelly sand at the base of the six-foot concretion bed forming the topmost Upper Greensand.

(3) The glauconitic sands with calcareous stone which in Devon characterise the basal Foxmould division persist throughout the Upper Greensand at Punfield.

(4) Chert beds are completely absent from the Isle of Purbeck sections and farther west, at Durdle Door (30/805803) and White Nothe, only a six-foot series occurs near the top of the Upper Greensand.

(5) The evidence of current activity seen in the higher beds of the Devon coast is lacking in east Dorset. At Ringstead (30/747819) small quartz pebbles up to 2 mm. in diameter occur in the top concretion bed. This passes westward into eight and a half feet of massive calcareous grit, again rich in fine quartz pebbles, exposed at Bincombe (30/688845). A similar grit free from pebbles occurs six miles to the west at White Hill, Abbotsbury (30/574860).

On the mainland the Upper Greensand thins eastward from 180 feet in Devon to only 40 at Punfield Cove, but between Dorset and the Isle of Wight important changes occur and in the south of the island the beds have thickened to over 100 feet. The sediments are here very fine-grained throughout, even in the highest horizons. Chert reappears in the succession, and at Culver Cliff (40/634855) twelve feet of Chert Beds occur six feet below the Chalk. At lower horizons the stone present is the hard white type known as 'Firestone' which, though sufficiently calcareous to react strongly with acid, has a largely chalcedonic groundmass. Siliceous stone of this type is lacking from the Devon and Dorset sections.

4. INLAND WESSEX

Columnar sections (Fig. 5) have been drawn to contrast the successions near Devizes, in the Vale of Wardour and at Chard, Somerset. Since present-day exposures are quite inadequate for the construction of these sections, they have been adapted from successions given by Jukes-Browne (1900), but utilising wherever possible additional information from the author's own field observations. The Upper Greensand beds of north-west Dorset have recently been fully described by Vernon Wilson *et al.* (1958) and need not here be considered in detail.

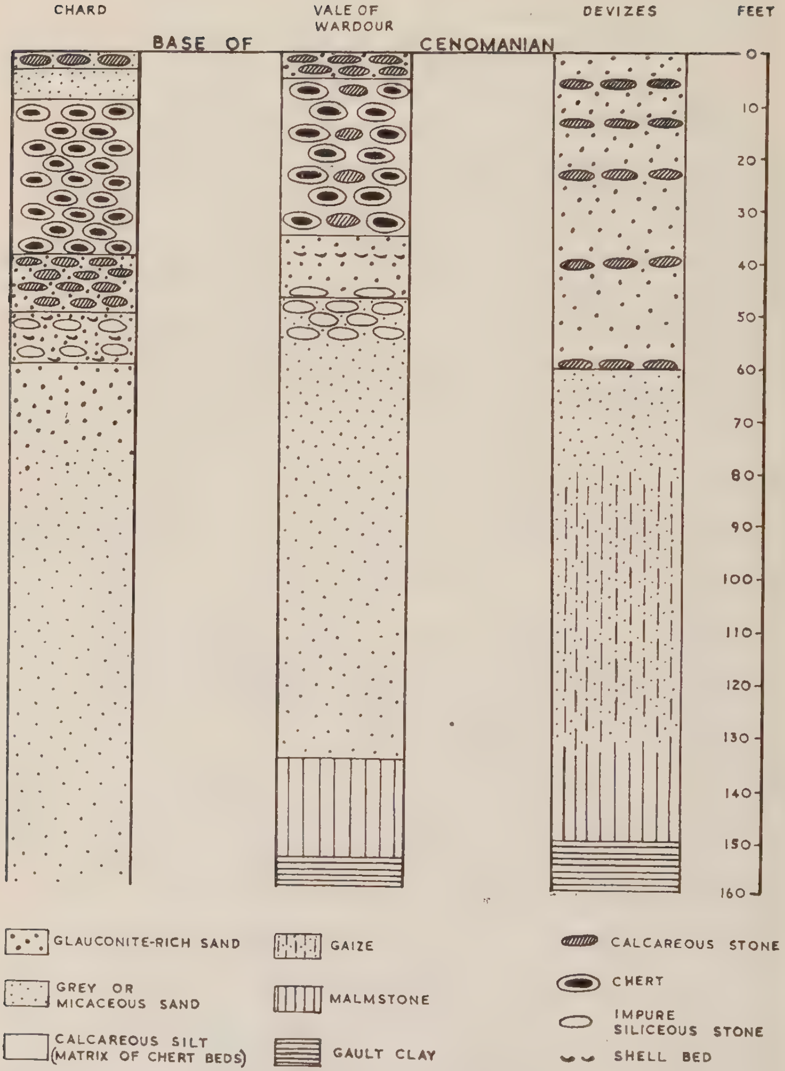


Fig. 5. Columnar sections showing the Upper Greensand succession in inland areas of Wessex

In Wiltshire the basal division of the Upper Greensand consists of the Malmstone—a fine siliceous rock completely different from anything seen on the coast. Very fine grains of quartz and glauconite, mostly of silt grade, are set in a siliceous groundmass which is almost isotropic in thin section, showing only a very incipient crystallisation. The Malmstone may be completely non-calcareous, but is more often rich in foraminifera and fine shell debris. Near Devizes it is overlain by a thick development of Gaize, characterised by a similar siliceous groundmass but with a much higher proportion of fine detrital grains. The Gaize is usually completely non-calcareous but occasionally contains large ovoid masses of calcareous stone. Traced south-west from Devizes it grades laterally into fine micaceous sands, as does the Malmstone itself south of Shaftesbury. The underlying Gault Clay thins out in west Dorset and near Chard the basal Albian consists of 120 feet of fine yellow sands, Jukes-Browne's 'Blackdown Sands', which are nowhere well exposed at present.

The columnar sections show that there is a general resemblance between the higher beds of the Upper Greensand of Chard and the Vale of Wardour. Chert beds occur at similar horizons in both areas and are almost identical in lithology, though very different from those of the coastal belt. The cored nodules of chert are set in a very fine sand, approaching a silt, which is very richly calcareous, sparsely glauconitic and completely non-ferruginous. The succession at Mere (31/803323) contains nodules of pure grey crystalline limestone which are lacking from the beds to the west.

In Somerset there are no Upper Greensand exposures north of the Chard district but from the Vale of Wardour the beds extend northwards into Wiltshire. The Chert Beds of Dilton (31/875492) differ from those to the south in that the groundmass consists of a fine-grained, non-calcareous, glauconitic sand. North-east of Westbury (31/877514) chert dies out completely to leave a series of glauconitic sands with occasional courses of calcareous stone, as shown on the Devizes section in Fig. 5. Chert is also absent from the Upper Greensand of north-west Dorset, dying out as the beds are traced south from Shaftesbury and west from Crewkerne.

The highest few feet of the Upper Greensand succession are everywhere chert-free. Inland, as on the coast, signs of current activity are most apparent in the west. In Wiltshire the highest bed is a glauconitic sand, grading up into the Glauconitic Marl of the basal Cenomanian, but in west Dorset it consists of a calcareous grit (the Survey's 'Eggardon Grit'), rich in small quartz pebbles and similar to that seen on the coast near Weymouth. At Snowdon Hill, Chard (31/313008), only a three-inch band at the top of the Upper Greensand contains quartz pebbles whereas three miles to the north-east at Chaffcombe (31/362099) six feet of coarse ferruginous grit occur, with quartz pebbles up to 5 mm. in diameter.

The Blackdown Facies. The zonal studies of Spath (1926) showed that the sediments of the Blackdown Hills pre-dated the Upper Greensand of other areas. Lithologically they are equally distinctive and what may be termed 'The Blackdown Facies' extends from Black Down itself (31/094072) eastward to Yarcombe (31/233079) and south-west to Peak Hill, Sidmouth (30/109867), giving a roughly triangular area of outcrop (see Fig. 1). The succession may be broadly subdivided into sands free from stone at the base, and overlying beds with chert and siliceous sandstone, both series being non-calcareous. The lower division is often a fine unconsolidated sand approaching the ortho-quartzitic, whereas the matrix of the Chert Beds consists of poorly graded sands, normally stained bright brown by limonite but with included streaks and patches of green non-ferruginous sediment. Glauconite is a prominent constituent of these sands, sometimes perfectly fresh, sometimes showing surface decomposition to iron oxides.

Erosion has removed both the Chalk and the highest beds of the Upper Greensand from this region and it seems probable that the leaching of all calcareous material from these sediments is due to the absence of a protective capping of Chalk. No calcareous stone is present and shells are either silicified or are preserved only as casts in the siliceous sandstone. Identical features are seen at Shute Hill (30/253987) near Axminster and at Hardown Hill, both localities from which the Chalk cover has been stripped. Thus it seems most likely that the leaching of calcareous material only took place in comparatively recent times when erosion had already removed the greater part of the Chalk from these areas.

Having briefly described the variations seen in the Upper Greensand successions of south-west England, the four components—glauconite, phosphate, limestone and chert—which characterise the division, can be considered in turn.

5. GLAUCONITE IN THE UPPER GREENSAND

Glauconite is almost invariably a component of both the Upper Greensand sediments and the concretions they contain. Though it may be present in equal abundance to quartz, it often occurs only in accessory amount (5–10%). Sparsely glauconitic sands are normally grey in colour but may be brown or buff as a result of subsequent iron-staining. True 'green sands' may be rich in glauconite but other factors are of equal importance: absence of iron oxides is essential, for these will completely mask the green coloration, and in addition slight green staining of the quartz grains can make an immense difference to the overall appearance of the sediment and can give a pronounced green colour to even moderately glauconitic types.

In Devon the glauconitic Foxmould Sands form the basal member of the Upper Greensand succession, but in Dorset the lowest arenaceous beds tend to be sparsely glauconitic. In Devon, Dorset and Wiltshire the sediments immediately below the chert-bearing horizons are especially rich in glauconite. The content of the mineral decreases sharply in the Chert Beds themselves while the coarse shallow-water sediments which form the highest beds of the Devon coast may be almost free from glauconite.

The lack of glauconite from the shallow-water sediments suggests that well-oxygenated waters were unsuited to the formation of the mineral. Reducing conditions do not appear to have been essential, however, since such diagnostic features as pyrite nodules are not generally characteristic of Upper Greensand sediments. Once formed the mineral is fairly stable and in most beds of the Upper Greensand the glauconite present is perfectly fresh. The grains occasionally show a surface disintegration to a sage-green powder, while decomposition to limonitic oxides is particularly characteristic of the Blackdown facies.

(a) Glauconite as a Mineral

In thin section glauconite shows the aggregate 'pin-point' birefringence characteristic of formerly colloidal minerals—the structure termed 'Metacolloidal' by Rogers (1917). The grains often contain minute inclusions which usually consist of quartz or calcite though accessory minerals such as muscovite can also occur. These impurities help to explain the diversity of the compositions assigned to the mineral in the literature. Glauconite is essentially a hydrated potassium–iron silicate, in which iron is partly replaced by aluminium and potassium by other bases. It is now generally agreed that no simple formula can be given for what may well be an isomorphous series rather than a single mineral.

Various types of glauconite are present in the Upper Greensand:

(1) Dark green opaque grains of rounded or botryoidal form.
(2) Glassy grains of varying shades of green, fine-grained and often of silt grade.
(3) Casts of organic remains.
(4) Replacing mineral grains.
(5) 'Pigmentary' glauconite staining pebble surfaces.

(1) Dark green opaque glauconite is the most common variety and invariably characterises those horizons rich in glauconite. The grains have a high surface lustre and are sometimes so dark in colour as to be almost black. They are usually found in sands of fine to medium grade as rounded, ovoid or botryoidal grains. Occasionally grains of coarse or medium grade are lobed types with deep surface cracks and these are believed to result from the contraction and desiccation of original gel material. Abrasion is thought to convert such glauconite to the more rounded grains characteristic of the finer grades.

(2) The glassy types occur as grains of silt or very fine sand grade, which are angular or irregularly rounded. Botryoidal and well-rounded grains such as characterise the opaque type are absent. The colour varies from a clear yellow tint through dull olive greens to bright emerald or grass green. All these vitreous grains are translucent, while the paler varieties may be completely transparent. It seems probable that such glauconite lacks the minute inclusions which so often characterise the dark green opaque variety of the mineral. A few grains of this type are often present in normal glauconitic sands but they are most characteristic of sediments which are (a) very fine-grained silty types and (b) only sparsely glauconitic. The Chert Beds of Somerset and the Vale of Wardour are cases in which almost all the glauconite present is of this type.

(3) Glauconitic casts of foraminifera may occur, though not in any abundance, and, in addition, the mineral may infill the pore-spaces of echinoid and holothurian fragments. More commonly the axial canals of sponge spicules are glauconite-infilled and a continuation of this process often leads to the complete replacement of the opaline silica of the spicules. The paler glassy varieties of glauconite occur in this form more commonly than does the dark green opaque type. No great significance can be attached to this, however, since the two varieties of glauconite may infill adjacent chambers of a single foraminiferal cast.

(4) A few examples of mineral grains which have undergone partial glauconitisation occur in the sediment. Quartz is most commonly affected; a glauconitic crust surrounds a quartz core of very irregular shape, which appears to have been corroded and replaced by the glauconite. Grains of plagioclase felspar in the sediments sometimes show slight glauconitisation along the cleavage planes and replacement of a highly decomposed mineral, possibly original potash felspar, may also be seen.

(5) Where limestone concretions have been subjected to abrasion on the sea-bed, they often show a marginal rim, up to a quarter-inch in width, which is stained green by glauconite. This impregnatory glauconite appears to be replacing fine calcareous mud since it occurs as dendritic patches within the groundmass and also infills the chambers of foraminifera, the crystalline calcite of their shells being unreplaced. Rounded sandstone pebbles in the higher beds of the Devon coast often have a thin surface coating of powdery glauconite, while shells and quartz grains found in richly glauconitic sediments may also be green-stained.

(b) Conditions of Formation

These various types of glauconite appear to have formed under different environmental conditions. The problem is complicated by the possibility of transport of the grains by currents, since the environment of formation may then be completely different from that in which deposition finally occurred. Only in the case of impregnatory glauconite is it reasonably certain that the two environments do coincide. During periods of penecontemporaneous erosion, limestone nodules were exhumed from the sea-floor sediments and subjected to rolling and abrasion which converted them to rounded pebbles. The process continued until the waning currents were no longer sufficiently strong to move the pebbles. It is clear that the glauconite-stained rim cannot have formed till this stage was reached, since any glauconite previously deposited would inevitably be removed by the continuing abrasion. The pigmentary glauconite appears to have been deposited from colloidal solutions adsorbed into the surface zone of the limestone. Thus glauconite was forming during the period following the main phase of current activity but while the pebbles were still exposed on the sea-floor. Subsequently, as deposition was gradually resumed, sediments rich in the dark green variety of glauconite were laid down in the still disturbed waters.

Though current action on the sea-bed may have favoured, and certainly did not inhibit, formation of the impregnatory and opaque varieties of glauconite, tranquil conditions appear to have been essential in the case of the glassy type. The fine silty sediments of which this variety is characteristic would form only where the currents were too weak to transport coarser detritus. The sheltered environment provided by the shells of organisms such as foraminifera also appears to have been more suited to the glassy than the opaque types.

The component elements required for the formation of glauconite were readily available in the Albian Sea. Dissolved salts would supply the potash required, while iron and silica would be leached from rocks undergoing chemical weathering, and transported to the sea in solution. In addition the halmyrolytic decomposition of granitic minerals such as biotite and orthoclase would further enrich the water in both potassium and silica. Mineral grains, the opaline silica of sponge spicules and fine calcareous mud could all undergo chemical replacement by glauconite, but most commonly the mineral originated as a gelatinous precipitate in sea-water.

The gel material sometimes stained the surfaces of pebbles and shells exposed on the sea-bed, but normally flocculated into small masses which hardened, contracted and partially dehydrated into true glauconite grains. Originally these would be lobed with deep surface cracks, but formation of glauconite at a time when currents were operative would inevitably result in transport and rounding of the newly formed grains. Deposition might occur as the current slackened but Hadding (1932) showed that the specific gravity increased as the mineral was converted from its original gelatinous state into true glauconite, and this alone might be sufficient to cause deposition. The grains then act as quite normal detrital constituents, and thus most of the Upper Greensand sediments contain glauconite and quartz grains of approximately equal size, the specific gravities of the two being similar.

6. PHOSPHATE IN THE UPPER GREENSAND

It is generally agreed that the very weak solution of phosphoric acid present in sea-water reacts on calcium carbonate to produce phosphatic nodules. This replacement is thought to depend on the presence of ammonium ions liberated by the decomposition of nitrogenous organic material on the sea-bed (Blackwelder *in* Twenhofel, 1926).

The nodules present in the Upper Greensand are usually dark brown or black in colour, but pale brown and cream-coloured types may also occur. Rounded, ovoid, rectangular or slab-like in form, they often show pitted surfaces in which pockets of the surrounding sediment are included. The original nature of many of the nodules cannot be determined but some are still recognisable as phosphatised molluscs or as limestone pebbles in varying stages of replacement. One nodule was clearly identifiable as an original sponge, the vascular nature of which was still preserved.

Small residual patches of calcite are preserved in the great majority of the Upper Greensand phosphatic nodules. In addition many nodules which appear at first sight to be completely phosphatised, prove on sectioning to contain a core of almost unaltered limestone surrounded by a marginal zone of collophane ($3Ca_3(PO_4)_2.nCaCO_3.xH_2O$). In the case of the phosphatised sponge already mentioned, the former vascules are infilled with collophane while the sarcode has been replaced by acicular dahllite ($3Ca_3(PO_4)_2.CaCO_3$). According to Rogers & Kerr (1942) the latter is invariably a secondary mineral following collophane.

Phosphatic nodules have a more sporadic distribution in the sediments of the Upper Greensand than does glauconite. They are particularly prominent in those beds rich in the dark green opaque type of glauconite, especially where these overlie depositional breaks. Such sediments are believed to form at times when current activity allowed only restricted deposition, these conditions being particularly favourable for two reasons:

(1) Shells and limestone pebbles on the sea-floor would be exposed to the influence of phosphatising solutions for a much longer time than they would during periods of normal deposition.

(2) Sparsity of other detritus increases the relative importance of both glauconite and phosphate in the sediments.

When pebbles of calcareous sandstone undergo phosphatisation, only the calcium carbonate is replaced, with the result that many phosphatic nodules contain numerous grains of both quartz and glauconite. In most beds of the Upper Greensand these grains are similar to those which comprise the surrounding sediment, but this does not hold true for the nodules present in the Glauconitic Marl, the basal bed of the Cenomanian.

Here the included mineral assemblage is often quite different from the associated sediment, being less glauconitic and usually finer-grained. In such cases the phosphatic nodules themselves may be derived from the Albian beds, though at Mere (where the highest Upper Greensand is phosphate-free) derived pebbles of limestone were subjected to phosphatisation on the Cenomanian sea-floor, being present in the deposit in all stages of replacement.

7. LIMESTONE IN THE UPPER GREENSAND

Though actual beds of calcite-cemented sandstone may occur, calcareous stone is usually developed as lenses or nodules within beds of sand—the type often denoted as 'doggers' or 'burrstones'. These are very widely distributed in the Upper Greensand though they are absent from the lower beds of the series in many inland areas of Wessex. Their former presence has already (page 326) been inferred in the sediments of the Blackdown Facies, which have subsequently been leached completely free from calcareous material.

Most calcareous concretions are packed with detrital grains and may be ascribed to the simple cementation by calcite of the surrounding sediment. The calcite is thought to be derived from fine shell fragments scattered through the deposit, and dissolved by slightly acid waters—a process which sometimes continued until all calcareous material had been leached out. Often, however, the calcite taken into solution was subsequently reprecipitated, to cement the sand into courses or isolated nodules of stone. During diagenesis, therefore, calcite will be dissolved from the more acid areas of a sediment and reprecipitated where conditions are more alkaline or, if the original solution was saturated, where they are less acid. Even slight variations of pH in a sediment can cause solution, migration and reprecipitation of calcite within it, so sensitive is the solubility of the mineral to these changes. It is clear that the process must have occurred at a very early stage, since the stone so formed was exhumed and abraded into pebbles during periods of penecontemporaneous erosion on the Albian sea-floor.

Pantin (1958) carried out radioactive (C^{14}) dating of a diagenetic calcareous concretion dredged up from seventy fathoms off the New Zealand coast. He concluded that deposition of the original sediment, segregation of calcareous material to cement part of it into sandstone and the subsequent exhumation during an erosional phase, probably took place within 7500 years, 19,500 years being the maximum period available. He believed that the localised reprecipitation was caused by the chance presence of a decomposing fish or mollusc which, under anaerobic conditions, liberated ammonia to cause a local rise in pH.

In addition to the detrital-rich types, nodules of pure limestone are also found, notably in the top concretion bed of the Upper Greensand and in the Chert Beds, where they often occur in banded alternation with the cherts themselves. In many of the more calcareous horizons of the series, detrital grains are of very sporadic distribution so that patches of fairly pure calcareous material are included. In rare instances where the limestone nodules have not been completely recrystallised, the groundmass may be identified as either finely disseminated shell debris or as a fine calcareous mud. The pure limestone nodules are thought to be formed when such calcareous patches within the sediment undergo recrystallisation. This process may also involve partial replacement of the quartz present since this mineral, which abounds in the surrounding sediment, is often virtually absent from the limestone. Where quartz does occur, it is quite unlike the normal sand, consisting of minute grains of very irregular shape which appear to have been subjected to corrosion and replacement by the surrounding calcite. Glauconite is not similarly affected, however, the grains, though few in number, being identical in size and shape to those in the associated sand. This corrosion of the quartz present distinguishes the pure limestones from the calcareous sandstones, which result from simple cementation of the sediment unallied to replacement.

8. CHERT IN THE UPPER GREENSAND

Upper Greensand cherts occur as isolated nodules or lenticular bands, six inches to one foot in thickness and aligned parallel to the bedding planes. A band of grey chert seen in a slipped mass below Haven Cliff reached the quite exceptional thickness of three feet but appeared to be of very limited lateral extent. The chert nodules normally consist of a massive flinty core, black, brown or grey in colour, surrounded by a band up to one inch in width of more porous stone. The latter is often white in colour but may be stained yellow or brown by iron. Nodules of porous light-coloured siliceous stone, resembling these marginal rocks but lacking the chert core, occur in the Chert Beds of the Vale of Wardour, Somerset and Hardown Hill, and in addition the Firestone bands of the Isle of Wight are also of this general type. Siliceous sandstone, absent from coastal areas, is developed in some inland regions, most notably in the Blackdown Hills; detrital grains, often including a high proportion of glauconite, are set in a chalcedonic groundmass.

Chert generally characterises the higher beds of the Upper Greensand succession, being absent from the lower part and also from the highest few feet of the division. The Chert Beds of the south coast consist of fine sands which are calcareous, glauconitic (but not richly so) and somewhat ferruginous. In the Blackdown Hills the sands have been leached completely free from calcareous material and this is also the case at Hardown Hill and

Peak Hill, Sidmouth. Such non-calcareous sediments are also more richly ferruginous than usual, suggesting that the leaching may have been accompanied by the decomposition of glauconite to limonite. The Chert Beds near Chard and in the Vale of Wardour consist of silt and very fine sand, richly calcareous but non-ferruginous and only sparsely glauconitic. The fine grain-size of these beds suggests deposition in a belt of very tranquil waters. There are three main lithologies from which cherts are absent:

(1) 'Green sands', rich in glauconite and free from limonite. Often such glauconite-rich beds immediately underlie chert-bearing horizons in which the content of the mineral declines sharply. A supply of silica in solution is believed to be essential for the production of both glauconite and chert, so that formation of one would inevitably restrict the formation of the other. Conditions on the sea-bed probably determined which of the two did in fact result, as a tranquil environment was ideal for chert whereas current activity would favour glauconite.

(2) Quartz-rich sands, such as characterise the highest beds of the Devon coast. These are calcareous and contain a little limonite (which imparts an overall honey colour to the sediment) but are very sparsely glauconitic.

(3) Beds showing evidence of current activity—this again being seen in the highest beds of the Devon coast. Such evidence becomes increasingly pronounced to the west, where cherts are progressively confined to the lower horizons of the series. To the east the reverse relationship is seen, and on the Dorset coast chert is developed only at the higher levels of the Upper Greensand which in Devon are completely free from chert.

Microscopic Features

In thin section the groundmass of the chert is seen to consist chiefly of botryoidal masses of chalcedonic silica in a metacolloidal state (a random aggregate of very fine fibres). These are of the type produced as a gel mass contracts during dehydration and were termed 'Colloform structures' by Rogers (1917). In addition the interstices between these masses have been infilled by radiate fans of acicular chalcedony. Detrital material is normally very sparse, but fine grains of quartz and glauconite, resembling those of the surrounding sediment and showing no sign of replacement, may occur. Organic remains are usually more abundant and spicules are invariably present, though the original opaline silica has reverted to the stable chalcedonic form. A few of the cherts contain an abundance of spicules but even these cannot be regarded as 'spicule-mats' of the type envisaged by Hinde (1885). Fine calcitic shell debris may be preserved unaltered or may be partially or wholly replaced by silica.

The features of the marginal rocks of the chert nodules are essentially similar. Colloform masses of metacolloidal silica again occur but the cavities between them are not here infilled by acicular chalcedony as is the case in the chert core. This partly accounts for the porous nature of the marginal rocks, though solution cavities are also characteristic. Former spicules are preserved only as casts in the siliceous grandmass and in many cases the calcitic shell debris has also been dissolved out. Detrital grains are again of little importance and the rocks cannot therefore be regarded as transitional types between the chert of the core and the surrounding sand.

As the author hopes to discuss the formation of these cherts in detail in a forthcoming paper, only a brief outline of the process envisaged will here be given. The seas of the Cretaceous period are believed to have been unusually highly charged with silica, due to the increased chemical weathering induced by a warm climate and low-lying land areas. Silica carried to the sea in solution was partly extracted by siliceous organisms such as sponges in building their skeletons, partly utilised in the formation of glauconite and partly precipitated as masses of silica gel. These solidified to give a porous rock which was subsequently converted into true chert by the deposition of silica derived from the solution of opaline spicules in the surrounding sands or from the margins of the nodule itself. The solution and reprecipitation of silica is thought to depend on slight pH variations within the sediment.

Chert formation was evidently a more prolonged process than that responsible for the limestone concretions. The pebble beds formed during periods of penecontemporaneous erosion never contain chert, even when they are developed within chert-bearing horizons. Presumably at this stage in the sediment's history the chert was still in the state of a soft gel mass and so disintegrated on exhumation.

9. LITHOFACIES

Each of the lithofacies maps (Fig. 6) represents a limited thickness of beds at a fixed distance below the base of the Cenomanian. The latter, approximately, though not always exactly, coincident with a zonal division and hence with a time-plane, is the only datum-line available, since Spath showed that the base of the Upper Greensand is markedly diachronous. This method can give only an approximate age-correlation, but no detailed zonal scheme has yet been produced for the Upper Greensand. The work of Spath (1926) is too imprecise for accurate correlation though lithological equivalents are given for four of his Upper Albian sub-zones:

5. *Pleurohoplites dispar-perinflatum* Sub-zone—Eggardon Grit of western Dorset.
4. *Pleurohoplites substuderi* Sub-zone—Chert Beds of western England.
3. *Pervinquieria aequatorialis* Sub-zone—Malmstone of western England.
2. *Pervinquieria auritus* Sub-zone.
1. *Pervinquieria varicosum* Sub-zone—Blackdown Upper Greensand.

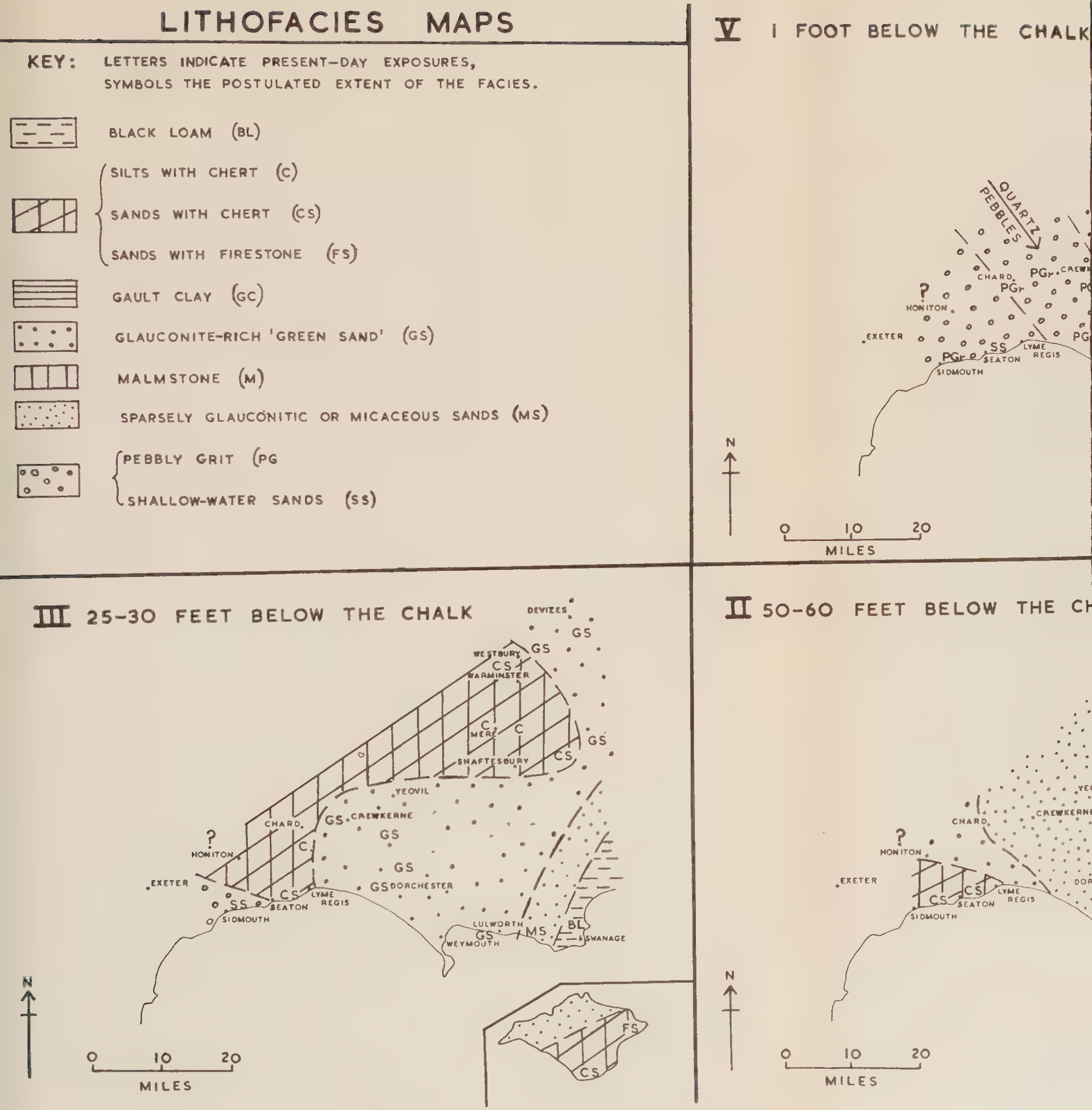
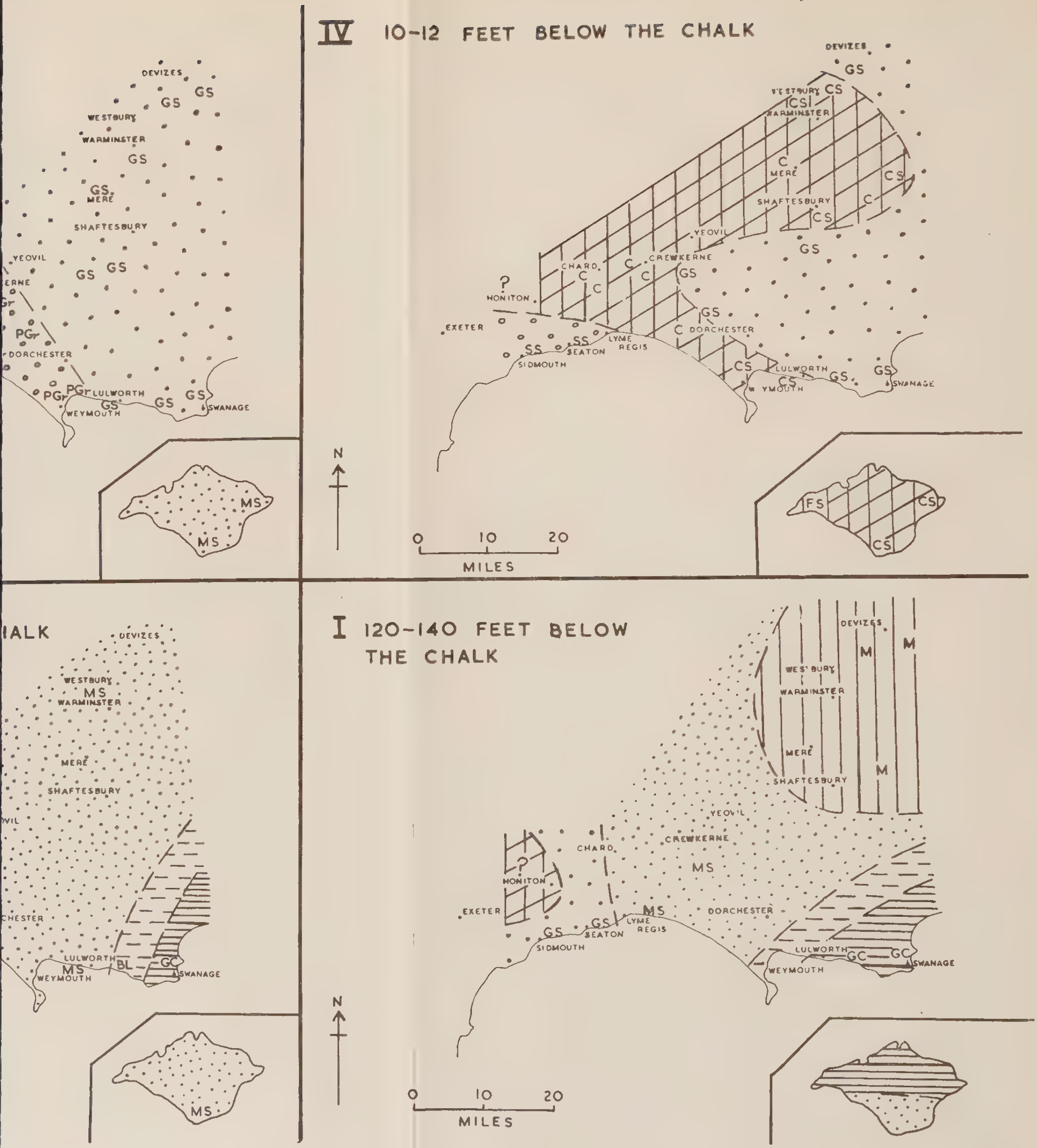


Fig. 6. Lithofacies maps for the Upper Greensand in We



IV 10–12 FEET BELOW THE CHALK

I 120–140 FEET BELOW THE CHALK

ssex (with insets showing the Isle of Wight)

[To face p. 334

This rudimentary scheme does demonstrate the important point that the Upper Greensand deposits of the Blackdown and Haldon Hills (where no datum plane is available owing to the absence of a chalk cover) predate those of more easterly areas.

In Spath's *Pervinquieria varicosum* Sub-zone, the Upper Albian Sea transgressed westward across southern England with the result that deposition of arenaceous sediment was initiated in Devon while Gault clays were still being laid down in Dorset, Wiltshire and south-east England. Subsequently the arenaceous facies began to spread eastwards; Fig. 6–I, based on beds 120–140 feet below the Chalk, shows the position at this stage (Spath's *Pervinquieria aequatorialis* Sub-zone). On the Devon coast, the glauconitic sands of the Foxmould series were being deposited, but inland ferruginous sands with chert may have been forming in rather shallower waters in the Blackdown region. In Wiltshire the Malmstone was in process of deposition, with micaceous sands in the region to the south and west. Gault Clay was still being laid down in east Dorset and also in the Isle of Wight, with the exception of the extreme south, where micaceous silts marked the transition to the arenaceous Upper Greensand.

Fig. 6–II is taken fifty to sixty feet below the Chalk, when chert was forming on the Devon coast but not elsewhere in the region. Malmstone had completely disappeared from Wessex, though it is present at this level in the western Weald. Grey sands, sparsely glauconitic and often micaceous, were deposited over much of the area, but the green glauconite-rich sands forming near Chard subsequently extended to the Vale of Wardour. Arenaceous sediments also characterised the Isle of Wight, though Gault Clay persisted at Swanage with a belt of black loam to the west at Worbarrow.

Horizons twenty-five to thirty feet below the Chalk are shown in Fig. 6–III. Chert formation may still have persisted near Seaton but had ceased on the coast to the west where shallow-water sediments were forming. Inland, in Somerset and the Vale of Wardour, silts were laid down in tranquil waters which were ideally suited to chert formation. To the south and east of this belt, glauconitic sands formed near Devizes and on the Lulworth coast, with black loams at Swanage. Chert beds characterised the south of the Isle of Wight, but in the west of the island glauconitic sands with calcareous stone still persisted.

The situation ten to twelve feet below the Chalk is illustrated by Fig. 6–IV. Chert formation had completely ceased on the Devon coast where shallow-water sands were now laid down. Fine calcareous silts with chert still characterised the Somerset–Wardour belt, and chert was also associated with the glauconitic sands of the central Dorset coast. Chert beds were now forming throughout the Isle of Wight, but in north and east Dorset and in the Devizes district, glauconitic sands free from chert were deposited.

In the highest Albian beds the position was much simpler and lithologies one foot below the Chalk are shown in Fig. 6–V. In the west the sands approach the orthoquartzitic and at Dunscombe very coarse shelly sands were formed. Quartz pebbles, well-rounded and up to 5 mm. in diameter, also occur in a NW.–SE. belt from Chard to the Weymouth coast; the general trend suggests that Exmoor might be a possible source. Glauconitic sands were being laid down in deeper seas in east Dorset and Wiltshire, with fine-grained, less glauconitic sediments in the Isle of Wight.

10. CONCLUSIONS

Jukes-Browne (1900), from a study of the molluscan fauna, estimated that the Upper Albian Sea was 200 fathoms in depth, while Kahn (1950) postulated 180 fathoms from the foraminifera present. There seems no doubt that the sea shallowed westward with the Upper Greensand deposited in the marginal tract. The fact that in so many areas the Gault passes up into Upper Greensand strongly suggests a shallowing of the sea towards the close of the Albian period, and this is confirmed by other lithological changes. However, in Devon the Upper Greensand, which predates that of more easterly areas, overlaps the Gault to rest directly on the Trias. Thus the earliest deposition of Upper Greensand immediately followed a westward transgression, and hence a probable deepening of the sea.

In Wiltshire the Gault is overlain by the Malmstone which occurs 150–160 feet below the Chalk and maintains a constant thickness of fifteen to twenty feet. It is clearly a diachronous formation, however, since in the Western Weald it occurs only eighty feet below the Chalk, while at Westerham the thin development of Upper Greensand consists entirely of Malmstone. The siliceous groundmass of the rock originated as a precipitate of amorphous colloidal silica, patches of which now show an incipient crystallisation. South of Shaftesbury the Malmstone grades laterally into arenaceous beds; in the Vale of Wardour it is directly overlain by fine sands but to the north-east the transitional Gaize separates the two. Thus clastic material seems to have spread across Wessex from the south-west, with chemical deposition persisting longest near Devizes. In the South Weald the Malmstone again shows a lateral passage into marly beds, so that it nowhere extends to the coastal belt, where current action caused mechanical rather than chemical deposition. Fig. 7 shows the total extent of the Malmstone as recorded by Jukes-Browne (1900). It will be seen that the bed is only developed along the line of the 'Wealden basin' which exerted a strong control over Lower Cretaceous sedimentation but was becoming less effective during the Albian. It seems significant that the facies only occurs in those areas where the Gault consists of a thick series of pure clays and is absent wherever the division is thin or sandy. It thus seems probable that the rivers and currents which carried the muds of the Gault may also have transported in solution the silica which, on precipitation, formed the groundmass of the Malmstone.

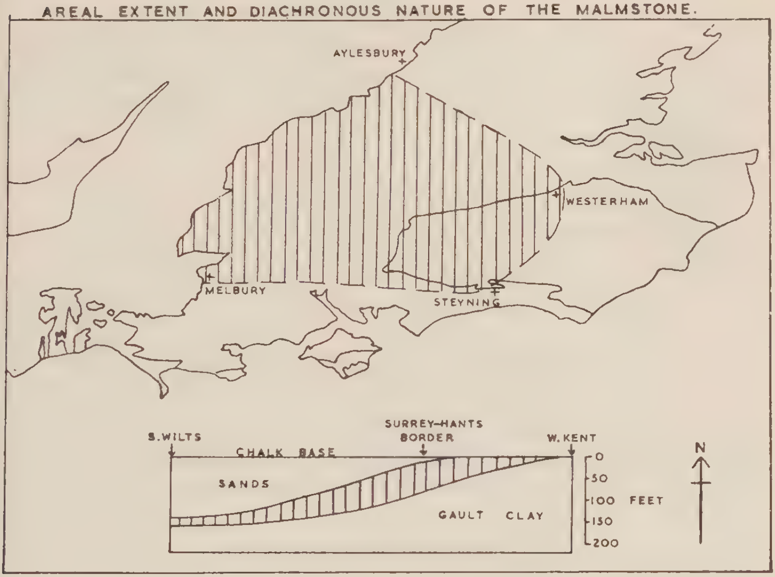


Fig. 7. Areal extent and diachronous nature of the Malmstone in southern England

The sequence clays–loams–sparsely glauconitic sands–richly glauconitic sands seen on the coast is indicative of shallowing waters, since glauconite formation appears to have been favoured by a certain amount of current action. The precipitation of the masses of silica gel which gave rise to the cherts required more tranquil waters, however, and did not occur during periods of marked current activity. The migration of the areas of chert formation (see Fig. 8) is thought to reflect the general shallowing of the seas towards the close of the Albian. In the highest Albian beds chert formation ceased altogether in England, although persisting throughout the Cenomanian in Normandy.

The beds of rounded pebbles, shell-banks and current-bedding which characterise the higher part of the Devon succession, all point to shallow current-swept seas. Strong currents must have been active in the Sidmouth, Chard and Weymouth districts at the close of the Albian period since numerous quartz pebbles occur in the sediments of these areas. In the deeper seas to the east, glauconitic sands were forming and there is here little distinction between the Albian and basal Cenomanian. No striking

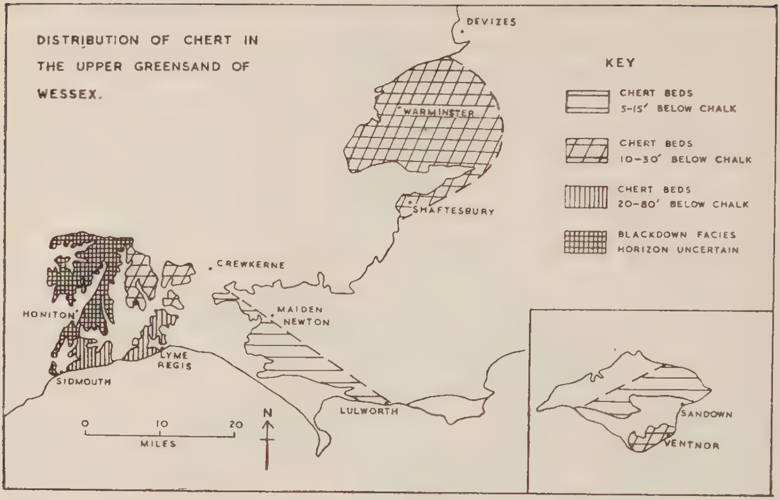

DISTRIBUTION OF CHERT IN THE UPPER GREENSAND OF WESSEX.
KEY
CHERT BEDS 5-15′ BELOW CHALK
CHERT BEDS 10-30′ BELOW CHALK
CHERT BEDS 20-80′ BELOW CHALK
BLACKDOWN FACIES HORIZON UNCERTAIN
DEVIZES
WARMINSTER
SHAFTESBURY
CREWKERNE
HONITON
MAIDEN NEWTON
LYME REGIS
SIDMOUTH
LULWORTH
SANDOWN
VENTNOR
0
10
20
MILES
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Fig. 8. Distribution of the Upper Greensand chert beds

palaeogeographic changes appear to have occurred in early Cenomanian times, and shallow current-scoured seas still persisted in Devon.

Source of the Sediment

The Albian Sea lay between two continental land-masses with the arenaceous sediment derived chiefly from the west. The Dartmoor mass was land, rising above the shallow-water deposits of the Haldon Hills, and supplied sediment, characterised by a distinctive heavy mineral suite, to the sea-basin to the east. This land-mass is known to have continued south into Brittany since King (1954) showed that the Albian, in common with the remainder of the Lower Cretaceous, is completely absent in the western part of the Channel. The abrupt thickening of the Upper Greensand between Dorset and the Isle of Wight, together with the marked differences between the two successions, strongly suggests that the latter area was not supplied with sediment from the west. A southern derivation seems an obvious inference in the light of the discovery by Groves (1933) of characteristic minerals from Brittany and the Cotentin Peninsula in these deposits.

Evidence of the presence of an eastern land-mass is seen in the thinning out of the Albian sediments against the Palaeozoic rocks of the Ardennes. Jukes-Browne suggested that this Belgo–Germanic land area was very low-lying and that the rivers draining it carried the muds of the Gault. It seems most probable that the silica which forms the groundmass of the Malmstone was carried in solution by the same rivers. The arenaceous constituents of the Upper Greensand seem to have been derived solely from the western land-mass.

ACKNOWLEDGMENTS

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REFERENCES

ARKELL, W. J. & C. W. WRIGHT. 1947. Geology of the Country around Weymouth, Swanage, Corfe and Lulworth. *Mem. geol. Surv. U.K.*

EDMUNDS, F. H. 1938. A Contribution to the Physiogeography of the Mere District, Wiltshire. *Proc. Geol. Ass., Lond.*, **49,** 174–96.

GROVES, A. W. 1931. The Unroofing of the Dartmoor Granite. *Quart. J. geol. Soc. Lond.*, **87,** 62–92.

HADDING, A. 1932. The Pre-Quaternary Sedimentary Rocks of Sweden. IV. Glauconite and Glauconitic Rocks. *Medd. Lunds Geol.-Miner. Inst.*

HAYWARD, H. A. 1932. Geology of the Lower Greensand in the Dorking–Leith Hill District, Surrey. *Proc. Geol. Ass., Lond.*, **43,** 1–15.

HINDE, J. G. 1885. Beds of Sponge Remains in the Lower and Upper Greensand of Southern England. *Phil. Trans.*, **176,** 403–53.

JUKES-BROWNE, A. J. 1900. The Cretaceous Rocks of Britain: Vol. I, Gault and Upper Greensand. *Mem. geol. Surv. U.K.*

——— & J. SCANES. 1901. The Upper Greensand and Chloritic Marl of Mere and Maiden Bradley. *Quart. J. geol. Soc. Lond.*, **57,** 96–125.

KAHN, M. H. 1950. Depth and Temperature of the Gault Sea. *Geol. Mag.*, **87,** 175–80.

KING, W. B. R. 1954. The Geological History of the English Channel. *Quart. J. geol. Soc. Lond.*, **110,** 77–100.

PANTIN, H. M. 1958. Rate of Formation of a Diagenetic Calcareous Concretion. *J. sediment. Petrol.*, **28,** 366–71.

RICHARDSON, J. A. 1947. Chert Formation in the Bargate Beds near Churt, Surrey. *Proc. Geol. Ass., Lond.*, **58,** 161–77.

ROGERS, A. F. 1917. A Review of the Amorphous Minerals. *J. Geol.*, **25,** 515–35.

——— & P. F. KERR. 1942. *Optical Mineralogy.* New York.

SMART, J. G. O. 1955. Geology of the Alton Pancras district of Dorset. *Bull. geol. Surv. G.B.*, **9,** 42–9.

SMITH, W. E. 1957. The Cenomanian Limestone of the Beer District, South Devon. *Proc. Geol. Ass., Lond.*, **68,** 115–35.

SPATH, L. F. 1926. On the Zones of the Cenomanian and Uppermost Albian. *Proc. Geol. Ass., Lond.*, **37,** 420–32.

TWENHOFEL, W. H. 1926. *A Treatise on Sedimentation.* London.

WILSON, V., F. B. A. WELCH, J. A. ROBBIE & G. W. GREEN. 1958. Geology of the Country around Bridport and Yeovil. *Mem. geol. Surv. U.K.*

The Discovery of Fluorite and Perovskite in the Upper Oxford Clay at Warboys, Huntingdonshire

by C. D. OVEY and P. GAY

Received 31 March 1960

RECENTLY a private expedition was made to Warboys clay pit to collect fossils, and a few lumps of clay were brought away and washed to examine the microfauna contained in the coarse residue. Amongst the residue were discovered black octahedral crystals sometimes twinned. These were sometimes associated with the much smaller pyrites crystals found in the cavities of small fossils such as minute gastropods and broken pieces of ammonite, but many were found free.

The lumps of clay were collected at random, some from *in situ* and some from the floor of the quarry. In any case the clay samples must have been derived from Spath's (1939) Ammonite zones—the lower *cordatum* and *lamberti* Zones.

In the Department of Mineralogy and Petrology, Cambridge University, some of the small octahedra were crushed, and an X-ray powder photograph was taken with CuKα radiation on a 9 cm. diameter camera. Measurement of the diffraction pattern showed that most of the lines were due to fluorite, although there were a few very weak lines which did not belong to this mineral. More careful examination of the crushed fragments revealed that the faces of the octahedra were coated with a thin layer of a dark material. An attempt was made to prepare a powder specimen from this coating. As very little of the material was available, photographs of this new specimen were taken with CuKα radiation upon a camera of 6 cm. diameter. Although the lines of the pattern obtained were predominantly those of fluorite, the extra lines were enhanced in intensity. The positions of these extra lines corresponded with the strongest lines of perovskite ($CaO.TiO_2$), and it seems probable that the dark coating of the octahedra must be identified with this mineral.

It would be interesting to know how widespread these minerals occur in the Oxford clay and whether they are to be found in other clays.

Samples of the crystals are deposited in the Department of Mineralogy and Petrology and in the Sedgwick Museum at Cambridge University, also in the Mineral Department, British Museum (Natural History).

The authors' thanks are due to the London Brick Company and their staff at Warboys for permission to enter their premises and collect material.

REFERENCE

SPATH, L. F. 1939. The Ammonite Zones of the Upper Oxford Clay of Warboys, Huntingdonshire. *Bull. geol. Surv. G.B.*, No. 1, 82–98.

Whitsun Field Meeting to Weymouth, Abbotsbury and Dorchester, Dorset

15–18 May 1959

Report by the Director: J. N. CARRECK

Received 29 January 1960

ON FRIDAY, 15 MAY, the party of twenty-three members and friends assembled at Weymouth. Transport throughout the meeting was by private coach.

Saturday, 16 May

The party drove to Old Castle Road, Wyke Regis, and walked to the shore about a quarter mile south-west of Sandsfoot Castle. There the Director explained the structure and stratigraphy of the district, emphasising that the Weymouth area consists essentially of Jurassic and Cretaceous rocks forming an asymmetric east–west anticline of mid-Tertiary date, with a gently dipping southern limb now greatly dissected by marine erosion, and a steeply inclined northern limb passing into a foresyncline overlain by Eocene sediments. This anticline pitches in an easterly direction and is continued by that of the Isle of Purbeck to the Brighstone anticline on the south-west coast of the Isle of Wight, where the Jurassic rocks have passed below sea-level.

The party then descended to the beach to examine the Sandsfoot Grits in the Upper Calcareous Grit (*Ringsteadia pseudocordata* Zone) near the top of the Corallian Beds. The Sandsfoot Grits consist of strongly ferruginous coarse sandstones, with concretionary structures of fucoidal appearance, and containing an abundant and varied fauna, chiefly of lamellibranchs. Unlike many other parts of the Corallian they were not deposited in a true coralline province. In the literature the predominant ammonites there are referred to the genus *Ringsteadia*, but in the writer's experience over sixteen years, by far the most common ammonite at Sandsfoot is *Microbiplices anglicus* Arkell. The grits there are about twenty-four feet in thickness. In the grits immediately south-west of Sandsfoot Castle one member found a well-preserved example of *Lingula* aff. *ovalis* J. Sow., determined by Dr. H. M. Muir-Wood. *L. ovalis* has been recorded previously from the Oxford Clay, Kimeridge Clay and Portland Beds, but not the Corallian Beds, in the Weymouth area. Indeed, the only other brachiopod recorded from the Corallian of that district is the new species *Discinisca sandsfootensis* Ager recently described from Sandsfoot (Ager, 1959). After examining the Sandsfoot Grits for some distance along the shore toward Castle Cove (675775),[1] and collecting examples of *Ctenostreon proboscideum* (J. Sow.), *Pecten* (*Chlamys*) *midas* Dollfus, *Pinna sandsfootensis* Arkell, *Pleuromya uniformis* (J. Sow.), and other fossils, from them, the party walked southward to the cliff below the railway cutting immediately north of Wyke Regis Halt (669766), where the shales of the *Rasenia cymodoce* Zone of the Lower Kimeridge Clay were examined and examples of the zonal genus obtained, in order that the Abbotsbury Iron Ore, on the same horizon, might be considered in relation to it later in the day. The Plateau Gravel overlying the Kimeridge Clay there was also noted.

Returning to the coach the party continued to Abbotsbury via Chickerell and Langton Herring, and the relation between geology and scenic features was pointed out at intervals. Alighting in the village square at Abbotsbury, members walked up Blind Lane past Jubilee Coppice (576856) to the water hole for cattle fed by a spring issuing from the Upper Greensand where the latter unconformably overlies clays of the Forest Marble. Water escaping at this junction causes extensive landslipping. Below could be seen Folly Hollow (575855), leading from Red Lane in the village. Folly Hollow is the site of Victorian iron ore working that proved uneconomic. The position and effects of the Intra-Cretaceous Abbotsbury Fault were described, including its action of throwing Corallian Beds and the Abbotsbury Iron Ore against Fuller's Earth and Forest Marble. This fault, with a throw of some 700 feet at Abbotsbury, affects only Jurassic rocks, and passes beneath the Upper Greensand west of Portesham. The Lower Greensand is absent from the district. The fault is thus seen to be of pre-Albian age.

The Abbotsbury Iron Ore was then described and in Blind Lane (576856) members obtained examples of the common *Ornithella* spp., *Rhactorhynchia pinguis* (Roemer), Rasenids, *Pleuromya*, *Pseudomelania*, etc. From there the party ascended Chapel Hill in order to see the physiographic features of the vicinity of Abbotsbury, notably the low-lying area of Oxford Clay and alluvium by the Swannery, Chesil Beach and the north-western termination of the Fleet lagoon. The origin of the beach and lagoon was the subject of a general discussion.

After lunch members drove to Dorchester via Portesham, noting the sarsens by the roadside at the latter and a pit in the presumed Bagshot Gravels on Blackdown.

At Dorchester members visited the Dorset County Museum in High West Street, where they spent a profitable hour in the geological section, seeing the unparalleled collection of Dorset fossils, and other geological material from the county, displayed there. All formations exposed in Dorset from Lower Lias to Holocene are represented, particularly the

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[1] The Grid References all lie within the 100 km. square 30 (S7T).

Jurassic rocks. The most notable features of the fossil collections are the reptilian remains from the Lias and Kimeridge Clay, the reptiles, fish and insects from the Purbeck Beds of the type locality, and the teeth of the Lower Pleistocene elephant *Mammuthus meridionalis* (Nesti), from Dewlish near Dorchester, the only known occurrence of this species in the south of England (Carreck, 1955, 171–2).

The party was welcomed by the Curator, Mr. R. F. Dalton, M.A., who gave a brief account of the museum before conducting the members round its other sections, devoted to Natural History and Archaeology. Leaving the museum, the party drove to the pre-Roman hill fort of Maiden Castle, about one and a half mile south-west of Dorchester. There members were shown the main features of the earthwork, and the foundations of the Romano–British temple and priest's house within its ramparts. The return journey to Weymouth was interrupted by a brief pause to see the slipped western side (672853) of the railway cutting at the southern end of the Bincombe Tunnel, where talus now obscures the well-known 'dyke' of Oxford Clay lying between the Jurassic and Wealden beds to the south and the chalk to the north, showing the close proximity of the east–west trending Abbotsbury (intra-Cretaceous) Fault and Ridgeway (mid-Tertiary) Fault.

Sunday, 17 May

The party devoted its attention to the Isle of Portland, the southernmost remnant of the southern limb of the Weymouth Anticline, composed of the upper 270–80 feet, approximately, of the Kimeridge Clay, overlain by the Portland Beds and the Lower Purbeck Beds, all with a dip of from 1 to 2° to the south. From Weymouth members traversed the Wyke Regis peninsula, composed of Corallian Beds and Kimeridge Clay, and Chesil Beach to Chesilton, Portland, at the foot of the Portland Beds escarpment, where members alighted in Victoria Square and ascended the storm beach at the extreme south-eastern end of Chesil. The Director gave an account there of the petrology of the beach and typical pebbles of porphyritic and granitic rocks and black cherts were collected, the original provenance of which was also discussed. Walking towards the West Weares members saw the sudden change from large beach pebbles to shingle in the last hundred yards of Chesil Beach, and the rubble of an ancient landslip, or Pleistocene head deposit, exposed in the cliff at Chesilton. A little farther south Kimeridge Clay was seen, on which no zonal work has been carried out but where shale with pyritised radial plates of the free-swimming crinoid *Saccocoma* has been collected recently, indicating the presence of the *Subplanites* Zone of the Upper Kimeridgian. Continuing southward, members collected from fallen blocks of Portland Sand and Portland Stone beneath the West Weares, before driving through Fortune's Well to

Priory Corner (688731). At the latter viewpoint, at about 375 feet O.D., the party's attention was drawn to the impressive north-westerly sweep of Chesil Beach past Abbotsbury to Burton Bradstock, with the brackish Fleet lagoon behind it from Abbotsbury to Wyke Regis, and the medieval course of the Fleet along its present position to Wyke Regis with no seaward connection, and between the Portland Harbour Beach and Chesil (which are now in contact) to its mouth at Castletown, Portland. The party continued to the Fossil Garden at the offices of the Bath and Portland Stone Firms Ltd., Easton, where members inspected fine examples of the larger Portland fossils: cycadeoids and conifers (*Araucarites*) from the Lower Purbeck Beds, and ammonites (*Titanites*) from the Freestone Series of the Portland Stone, in addition to stalagmite from fissures in the latter. The party then drove to Portland Bill, pausing to inspect Culver Well, a powerful spring rising in the Lower Purbeck Beds about four-fifths of a mile north-east of the Bill. At the latter, by permission of the Admiralty, the party first visited the section (675683) in Late Pleistocene Head and Loam, overlying the Raised Beach deposits assigned to the Main Monastirian sea-level, west of the present lighthouse. The Director gave an account of these deposits and members devoted about thirty minutes to their examination, collecting erratics from the Raised Beach and Pleistocene non-marine mollusca from the Head and Loam. Debris in the Head and Loam, derived from the Middle Purbeck Beds, no longer occurring on Portland, shows the local presence of these beds during the Last Glaciation. After lunch the cliff-edge exposure of the Raised Beach (679685) just east of the lighthouse was visited and members found numerous examples of the common *Patella*, *Littorina* and *Neritoides* together with a few shells of *Tectura virginea* (Mull.), *Gibbula*, etc., and contemporaneous crypts of the Polychaete annelid *Polydora* in limestone pebbles, common there.

Just below twenty-five feet O.D., close to the modern lighthouse, the physiographic features of the locality, including the limestone sea-stack known as Pulpit Rock (676683), were pointed out. The party next drove to Church Ope, to see the Cherty Series of the Portland Stone exposed immediately beneath Rufus Castle (Edmunds & Schaffer, 1932, pl. IIA), built during or soon after 1080, the oldest known building of Portland Stone still standing. There a 'giant' Perisphinctid ammonite was seen *in situ*, together with abundant molluscan shell debris but few whole shells or valves, indicative of current action. Members next entered St. Paul's Quarry (698715) of the Bath and Portland Stone Firms Ltd., immediately north of Rufus Castle, at Wakeham. There an extensive section in the Freestone Series of the Portland Stone, and the Lower Purbeck Beds, is available. The Portland quarries do not show the Cherty Series of the Portland Stone as, generally speaking, the abundant chert renders the stone unfit for building, and so this series has only been used occasionally, in the island. In a cutting entering the southern side of the quarry, where the 'slat' (fissile fine-grained cream-coloured limestone, near the top of the local Lower Purbeck Beds) is exposed, members found an insect, determined by Professor F. E. Zeuner as one of the Hemiptera, and ostracods determined by Professor P. C. Sylvester-Bradley as '*Candona*' *bononiensis* Jones in abundance with a few of an undescribed genus and species. All three forms are new records for the Lower Purbeck Beds of Portland. Proceeding farther into the quarry members examined the commercially important beds of Portland Stone and collected the common Portlandian mollusca from them: *Trigonia gibbosa* J. Sow., *Plicatula lamellosa* Cox, *Eodonax dukei* (Morris & Lycett), *Lucina portlandica* (J. de C. Sow.), and *Aptyxiella portlandica* (J. de C. Sow.), from the Roach at the top of the Portland Stone, together with fragmentary *Isognomon listeri* (Fleming), *Pecten* (*Chlamys*) *lamellosa* (J. Sow.), etc., from other beds. Some members interested themselves in some fissures exposed in this quarry, and in one of these a member found splendidly developed honey-coloured 'dog-tooth' calcite. Also in this quarry a recently exposed area of dirt bed was seen, a fossil soil layer in the Purbeck Beds, and some members recovered from it some of the peculiar pieces of limestone mentioned by Arkell (1947, 125). A considerable time was devoted to an examination of this quarry, after which members walked along Grove Cliff to the Borstal Institution (formerly Portland Convict Prison), seeing magnificent views of the undercliff and Weymouth Bay. The width of this portion of the undercliff increases to as much as one-sixth of a mile and forms a gently sloping but boulder-strewn surface obscuring much of the outcrop of the Kimeridge Clay and Portland Sand, at the foot of vertical cliffs of Portland Stone rising about 150 feet to the 300 foot contour. At the junction of the Kimeridge Clay and Portland Sand is a spring line, and landslips in Portland are caused by lubrication of this junction by percolating water after long-continued heavy rain, together with other factors. The undercliffs of the island are strewn with the products of land-slipping and subaerial erosion of the cliffs above, with debris tipped from the quarries in many places.

Monday, 18 April

This morning the party travelled from Weymouth to Langton Herring coastguard station (606814), where the Director explained that members were standing at the core of the Weymouth anticline on the oldest rocks exposed in the Weymouth district, the Upper Fuller's Earth. The low cliff on the adjacent Fleet shore shows from six to twelve feet of the Langton Herring Oyster Bed in the Upper Fuller's Earth Clay, composed entirely of *Ostrea hebridica* Forbes and its variety *elongata* Dutertre, except for a few fragments of an undetermined *Pecten*. From the coastguard station the party followed the shore south-eastward, past another small exposure of the Oyster Bed to the small peninsula of Forest Marble clays and limestones known as Herbury. On the north and north-west shore was a scatter of well-preserved fossils, chiefly such brachiopods as *Goniorhynchia boueti* (Dav.), *Digonella*, *Avonothyris langtonensis* (Dav.), and small gastropods, lamellibranchs, polyzoa, etc. Most come from the remarkable *G. boueti* Bed at the base of the Forest Marble. On the southern side of Herbury the fissile limestone which lies about the beach in quantity shows marked signs of deposition in shallow water, including molluscan shell debris, polyzoa, annelid tubes and many columnals of *Apiocrinus*. Mr. H. M. Montford found a slab bearing sinuous rows of indentations, which, Dr. R. Casey suggests, may have resulted from strings of gas bubbles passing through the calcareous mud of Bathonian times. At the SSW. tip of Herbury Mr. F. H. A. Engleheart, M.A., obtained an Hexacoral from the Forest Marble, determined by Dr. H. Dighton Thomas as *Isastraea limitata* (Lamx.) and presented to the British Museum (Natural History) by the finder. This constitutes a new record for the locality.

The party then drove to Crook Hill Brickyard, Chickerell, in Lower Oxford Clay (645799). This pit is in clays and shales with septaria, belonging to the *E. coronatum* and *P. athleta* Zones of the Callovian. Septaria lie on the floor of the workings in addition to being seen in great numbers *in situ* in the pit face, which is about seventy feet in maximum height. The fallen septaria yield lemon-yellow calcite filling their radiating fissures, and selenite associated with pure-white pulverulent anhydrite on their outer surfaces. After a brief description of the stratigraphical sequence in the pit by the Director, members examined the workings, chiefly searching in Bed 2 (*E. coronatum* Zone shales) of Arkell (1947, 29) in the southern part of the pit, in which they found the usual crushed examples of *Cosmoceras*, *Nucula*, *Procerithium* and *Dicroloma*, with uncrushed tubes of *Serpula vertebralis* J. de C. Sow. Dr. F. H. Moore had the good fortune to obtain a dibranchiate cephalopod determined by Dr. Casey as *Geopeltis brevipennis* (Owen), one of the Teuthoidea, now donated to the Geological Survey Museum by the finder, and Mrs. Carreck and others discovered a fragmentary teleostean fish, referred to *Leptolepis macrophthalmus* Egerton by Dr. B. G. Gardiner of Queen Elizabeth College. The cephalopod and fish have not been recorded previously from the Oxford Clay of this district although similar examples have long been known from the Lower Oxford Clay of Christian Malford, Wilts. Members also found uncrushed whorl fragments of *Peltoceras* loose in the pit, fallen from the upper part of the *P. athleta* Zone.

Finally the meeting, which had been favoured by excellent weather throughout, was brought to a close. Dr. Moore proposed a vote of thanks to the Director and to Mrs. Carreck as Secretary to the meeting.

REFERENCES

AGER, D. V. 1959. A New Inarticulate Brachiopod from the Dorset Corallian. *Proc. Geol. Ass., Lond.*, **70**, 28–30.

ARKELL, W. J. 1947. The Geology of the Country around Weymouth, Swanage, Corfe and Lulworth. *Mem. geol. Surv. U.K.*

CARRECK, J. N. 1955. The Quaternary Vertebrates of Dorset, Fossil and Sub-Fossil. *Proc. Dorset Nat. Hist. & Arch. Soc.*, **75**, 164–88.

EDMUNDS, F. H. & R. J. SCHAFFER. 1932. Portland Stone; its Geology and Properties as a Building Stone. *Proc. Geol. Ass., Lond.*, **43**, 225–40.

White Watson (1760–1835) and His Geological Sections

by TREVOR D. FORD

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ABSTRACT: Overlooked by most works on the history of geology, White Watson is shown to be a pioneer in the study of Derbyshire stratigraphy, although relatively little of his researches appeared in print. Much more was publicised in the form of inlaid marble 'Sections of Strata', or in lectures and discussions in his museum-shop in Bakewell. His extensive collections were the basis of much early palaeontological work. His outlook on geology and his influence on contemporary geological thought are assessed.

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1. INTRODUCTION

A Delineation of the Strata of Derbyshire, forming the surface from Bolsover in the East to Buxton in the West, by a plate designed from a Tablet composed of specimens of each stratum within the above line with an explanatory account of the same, together with a description of the fossils found in these strata and also of the nature and quality of the respective soils, by White Watson, F.L.S., Sheffield, 1811. Such was the cumbersome title of one of the first comprehensive works on the geology of Derbyshire. The first volume of Farey's great work on the Agriculture and Minerals of Derbyshire was published in the same year, but the former was an expanded version of Watson's earlier work published as a pamphlet some twenty years before (1788). Only Whitehurst (1778 and 1786) preceded Watson, although his writings on Derbyshire were but the appendix to a larger work. Mawe's *Mineralogy of Derbyshire* (1802) preceded Watson's expanded version but only dealt with certain aspects of the subject.

Watson's book (1811) is rightly considered as one of the foundations of geological knowledge in the Midlands but neither he nor his works have received due recognition, only Edwards (1931) and Challinor (1947) placing him in proper perspective.

His published sections were among the first reasonably accurate geological sections as we know them to appear in Britain, and his unpublished sections display a wider knowledge of stratigraphy than many contemporary and later publications. Of the former several appeared only in the form of inlaid marble 'Tablets', which, although 'published', would not normally be found in literary collections.

This study was undertaken as a result of facts uncovered during the writer's recent study of the Ashford Black Marble industry (Ford, 1958) with which White Watson was intimately connected.

2. FAMILY HISTORY

White Watson was by profession a sculptor, marble-worker and mineral-dealer, residing for most of his life in Bakewell, Derbyshire. He was born at Whiteley Wood Hall, near Sheffield, on 10 April 1760, the son of Samuel Watson of Baslow, Derbyshire, a millstone manufacturer. Both his grandfather and his great-grandfather were also named Samuel Watson and both were stone-masons and sculptors engaged at times in the rebuilding of Chatsworth House in the late seventeenth and early eighteenth centuries. White Watson's uncle, Henry Watson, established the water-powered marble mill at Ashford-in-the-Water and was one of the founders of the Blue John and Ashford Marble trades in Derbyshire (Ford, 1958). His mother was Martha, daughter of Joseph and Deborah White, whence the unusual Christian name. During his boyhood White paid frequent visits to his uncle's marble mill and shop, and from an early age took an interest in the small collections of fossils and minerals which his uncle sold from time to time. He kept his uncle supplied by visiting local quarries and mines and soon started his own collection. He left Sheffield School at the age of fourteen and on 31 May 1774 went to live with his uncle who had retired to Bakewell the year before. For some years he helped to carry on his uncle's business and in 1782 advertised himself as a sculptor and engraver. Henry Watson died in 1786 and the marble mill was sold so that White was thereafter a dealer and finisher of marble products only. He sold his products together with Blue John and alabaster in his museum-shop where he kept his collections and gave lectures, etc. In 1825 his card listed 'executes monuments, tombs, etc., gives lessons in geology and mineralogy and furnishes collections, affords information to antiquaries and amusement to Botanists'. He was elected a Fellow of the Linnean Society in 1795 and remained so until his death.

In 1808 White Watson, then forty-eight years of age, married Ann, daughter of Daniel Thorpe of Buckminster, Leicestershire, a relative of

Sir Isaac Newton's family. She was then twenty-nine. They lived in the Bath House in Bakewell, built over one of the warm springs. There were no children and Ann died in 1825. Ten years later White followed, on 8 August 1835. He was buried in Bakewell Churchyard.

3. HIS CHARACTER

From a perusal of White Watson's diaries and the other manuscripts certain clear facts emerge about his life. Firstly, there is no mention of any journey of more than about twenty-five miles from Bakewell, and even visits to places as near as Sheffield, Chesterfield, Matlock and Leek were infrequent. To judge from the records, he does not even seem to have visited his wife's home in Leicestershire! On the other hand he knew the area around Bakewell extremely well. Secondly, he never seems to have had much money, and on at least two occasions borrowed £100 from the Duke of Devonshire. He did not have much business sense but somehow managed to make a living. Thirdly, he took an active interest in local affairs, and considered himself one of the gentry. Although he favoured their company, he does not appear to have held office on any local councils or committees. Fourthly, he had a wide circle of correspondents with many of whom he exchanged specimens and, probably, geological ideas. He appears to have been fairly widely versed in contemporary geological and botanical literature although he rarely bought any books. He evidently had access to the library in Chatsworth House.

Few notable travellers in Derbyshire with any interest in natural history failed to visit him in Bakewell and most of them entertained him to dinner at the Inn. Two have left brief descriptions of his appearance and character.

Lord Denman (Axon, 1879) commented favourably on his knowledge and method of acquiring it and the laying out of his collections, and mentioned the encouragement he had received from Wedgwood and Sir Joseph Banks. Hunter (1804) wrote after meeting him once: 'Mr. Watson was rather below the middle stature with a pug-face, is a bachelor and takes his glass of spirits and water at the Inn in Bakewell every evening. Dakeyne (a local worthy?) gives him this character—he is in general a very worthy man but withal one of the greatest liars he knows. . . .' This last comment may refer to his disbelief in Watson's geological discourses as it is not mentioned elsewhere.

White Watson described himself as a sculptor and geologist but his manuscripts indicate a much more varied occupation. As a sculptor he was intermittently engaged in work on memorials and tombs. He restored the Foljambe tomb in Bakewell Church and did a considerable amount of work for the Sitwells at Renishaw. He made an inlaid plaque for St. George's Chapel at Windsor to commemorate the restoration to health of

George III in 1789. He advertised himself as Estate Mineral Surveyor, who would examine the distribution of strata and advise on their agricultural properties. He would supply the materials for gentlemen to build grottos. He cleaned paintings and even engraved a dog-collar!

When not otherwise occupied he made marble and spar ornaments for sale in his museum-shop. Occasionally he bought slabs of marble from Ashford to finish to specification. At times he employed men in his workshop, but the records are not clear as to how many or how often. He was constantly improving his collections and sometimes paid miners for choice specimens. He built up collections of up to 500 specimens several times over—enough to have printed catalogues. One such was sold to the Leskean Museum in Dublin for £34 2*s.* 6*d.* in 1805. His own collection was open to view for a small charge and he gave lectures on geology in his museum—usually at five shillings a head!

White Watson was noted locally for his ability to draw profiles of people, either in ink or as marble inlays. From time to time he wrote poetry, usually with a geological theme:

On Gregory Mine, Ashover (1812)
Pellucid fluor midst wat'ry shades displays
Iron pyrites, bright with lightning's vivid rays.
The cubic walls Zinc marks with sable ore,
And bright galena laminates the floor.

On the Screwstone (Crinoidal Limestone) (*c.* 1821)
Though I seem as a screw
Which to you comes in view,
Please to pardon my wise definition:
Calcareous I've been,
Though in silex now seen,
Hard enough is my curious transition.

Part of a poem entitled *Bolsover* (1812)
Beneath the hill inquiry late disclos'd
The spot, where, deep conceal'd the Coal repos'd;
But jealous agriculture clos'd the ground,
Nor suffer'd trade to break its sleep profound.

Sculptor, stone-mason, marble-worker and dealer, engraver, geologist and mineralogist, author, poet, lecturer—White Watson was a man who liked variety.

4. WHITE WATSON AS A GEOLOGIST

White Watson's publications give a very inadequate picture of his geological attainments. Only two of his detailed sections appeared as plates in his books. Several others appeared as marble-backed inlays of the various strata represented, which Tablets, as he called them, were soon separated from their explanatory pamphlets and became more or less unintelligible. Other sections are known only in manuscript. Although well over 100 tablets were made only fourteen are known to the author.

White Watson prepared his first tablet in or before 1785. It was sent to Whitehurst in January 1786, so Watson probably drew some inspiration from Whitehurst. This first tablet was of 'A Section of a Mountain in Derbyshire' (Fig. 1). It was apparently intended to be a generalised section

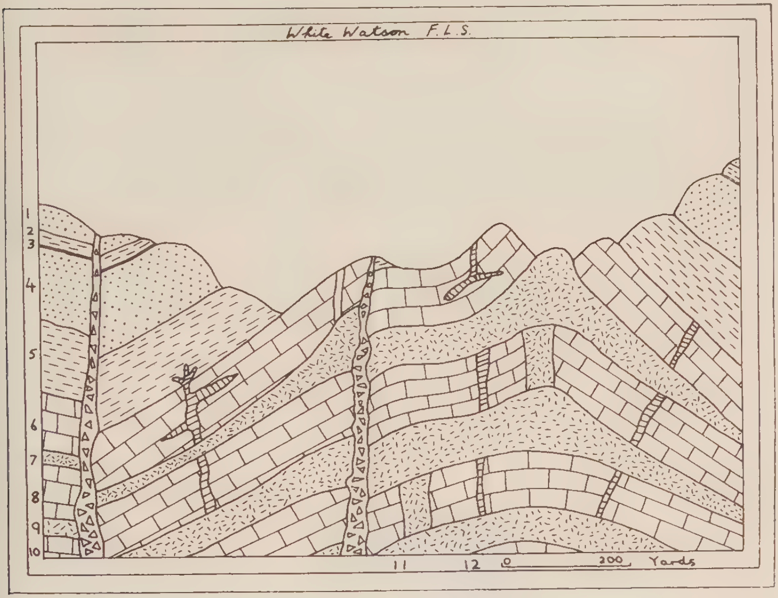


Fig. 1. 'A Section of a Mountain in Derbyshire.' A reproduction of White Watson's first tablet, made about 1785. (Based on tablet in Derby Museum.) Key from White Watson (1788):

1. Argillaceous grit.
2. Argillaceous Ironstone.
3. Coal.
4. Siliceous Grit.
5. Shale with lead ore from the Limestone.
6. Limestone with a pipe-vein and two rakes.
7. Toadstone.
8. Limestone with two rake-veins and a vein of toadstone.
9. Toadstone with a rake-vein of ore.
10. Limestone with rake-veins of ore and one of toadstone.
11. Toadstone.
12. Limestone with a rake-vein of ore and one of toadstone, corresponding with the above rake-vein of ore.

'The Scale of Yards at the bottom is for determining the depth of the strata. One chief design of the Tablet is to show, whatever stratum may happen to be uppermost, the general arrangement of the subsequent strata' of Derbyshire, not a specific locality (tablets are in British Museum (Nat. Hist.) and Derby Museum). In it he recognised three groups of limestone beds with different properties and 'mineral and fossil productions', separated by toadstones, penetrated by rake-veins and broken by faults. These were all thrown into an anticline with gritstones and shales dipping off either side. He followed Whitehurst in realising the meaning of a succession of strata in terms of forecasting what would be found beneath surface beds but went further by establishing the basic stratigraphical succession in Derbyshire (Fig. 1), Whitehurst having restricted most of his work to the Matlock area. He portrayed the rake-veins as continuous in the limestones above and below a toadstone although absent from the latter. Faulting displaced the beds and was accompanied by strong brecciation. He again followed Whitehurst in requiring strong fractures, usually widening downwards, in the axes of synclines. Only in his later years is this corrected. Nowhere in the description of this or later sections is there clear indication that he realised that his structures were folds. Later

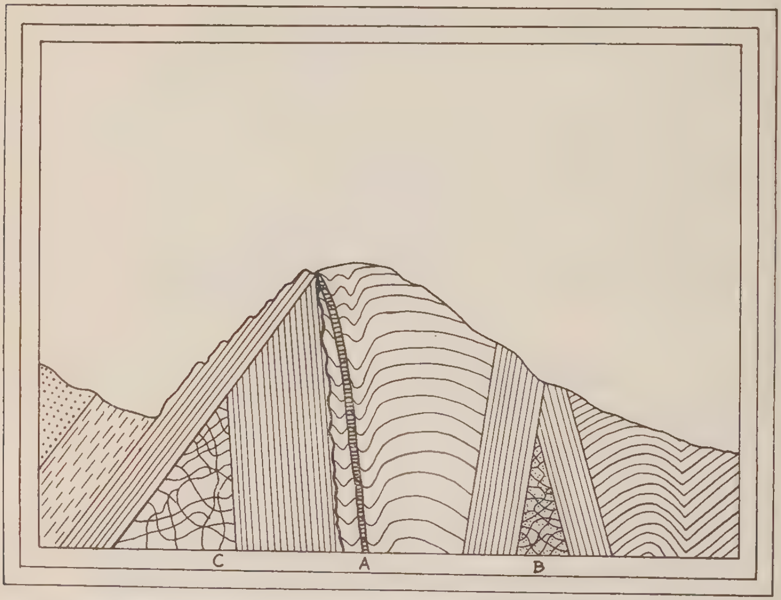
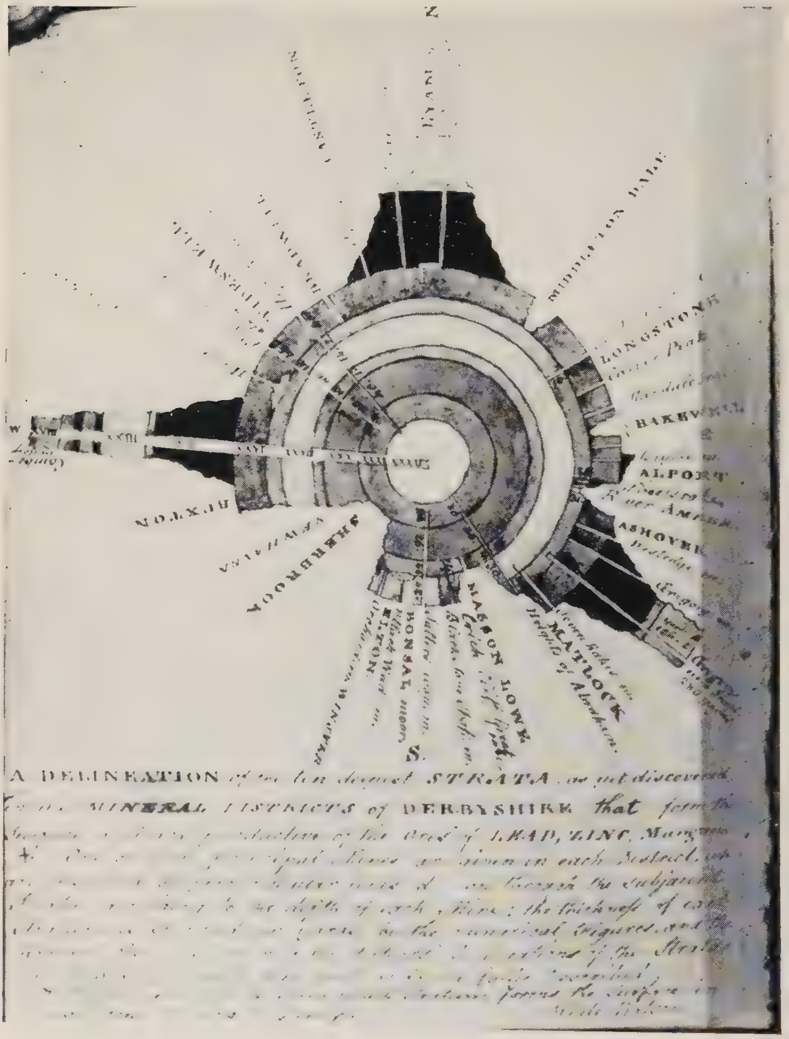


Fig. 2. 'A Section of the curious curvilinear Strata at Ecton Hill.' White Watson's interpretation of the section in folded limestones at Apes Tor, near the Derbyshire–Staffordshire border, made about 1794. (Based on tablet in Derby Museum.)

A. a vein of copper ore.

B. a lum, which is a species of stone different from that of the rock itself and injected betwixt strata.

C. a quantity of refuse drawn out of the mine


N.
MIDDLETON DALE
LONGSTONE
BAKEWELL
ALPORT
ASHOVER
MATLOCK
MASSON
LOWE
BONSAL moor
ELTON
S.
SHERBROOK
W
A DELINEATION [illegible] STRATA [illegible] yet discovered
[illegible] MINERAL DISTRICTS of DERBYSHIRE that [illegible]
[illegible] LEAD, ZINC, [illegible]
[illegible] given in each District [illegible]
[illegible] the thickness of [illegible]
[illegible] the numerical Figures, and [illegible]

White Watson's circular stratigraphical correlation diagram. *c.* 1825. Key on Fig. 4. Original in Derby C.B.C. MS. 8371. [The shaded portion on the right-hand edge is due to a repair to the original] he called them 'conical hills' forced upwards by the pressure of uprising lavas. Thicknesses of the strata, somewhat exaggerated, were shown in a scale on the margin of the Tablet.

Later sections of strata (Figs. 2 and 4) show gradual improvement in stratigraphical detail and localisation of phenomena represented. About 1797 a Tablet was produced depicting 'A Section of the curious curvilinear Strata at Ecton Hill' (of copper mine fame) on the Derbyshire–Staffordshire borders (Fig. 2). Some copies of this were on the backs of 'A Mountain in Derbyshire' tablets (as in British Museum (Nat. Hist.) tablet); others were separate (e.g. Derby Museum). The Ecton Hill section was a portrayal of the well-known section in folded limestones at Apes Tor on the northern flank of Ecton Hill, and it is roughly comparable with that in the Geological Survey Memoir (Green, 1869, 37), which is, however, curiously reversed.

The publications accompanying these early sections show that Watson was already familiar with William Smith's principle of strata being characterised by certain fossils, although he did not take the next step of using fossils to identify his strata in Derbyshire—a difficult matter even at the present time.

About 1797 Watson prepared his only section dealing with an area wholly outside Derbyshire—Bewerly Liberty, near Pateley Bridge, Yorkshire (not Beverly as given by Edwards, 1931, 64) (Fig. 3). Examples are in

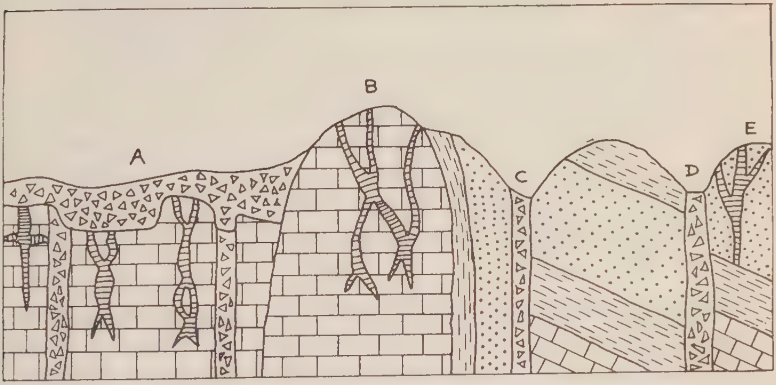


Fig. 3. 'A Section of Bewerly Liberty, Yorkshire.' White Watson's only section of an area outside Derbyshire, made about 1797. (Based on tablet in Derby Museum.)

A. Galloways—limestones with gulphs, broken and with different inclinations.
B. Greenhow Hill—same limestones as at Galloways in hemispherical beds which form the surface.
C. Lead mills and level tails—a valley for the contents of levels to be taken out and washed, etc.
D. Prosperous Mine—sandstone is on north cheek of vein, which is apparently in a gulph.
E. Sandstones with rake-veins. Also called Stony Groves

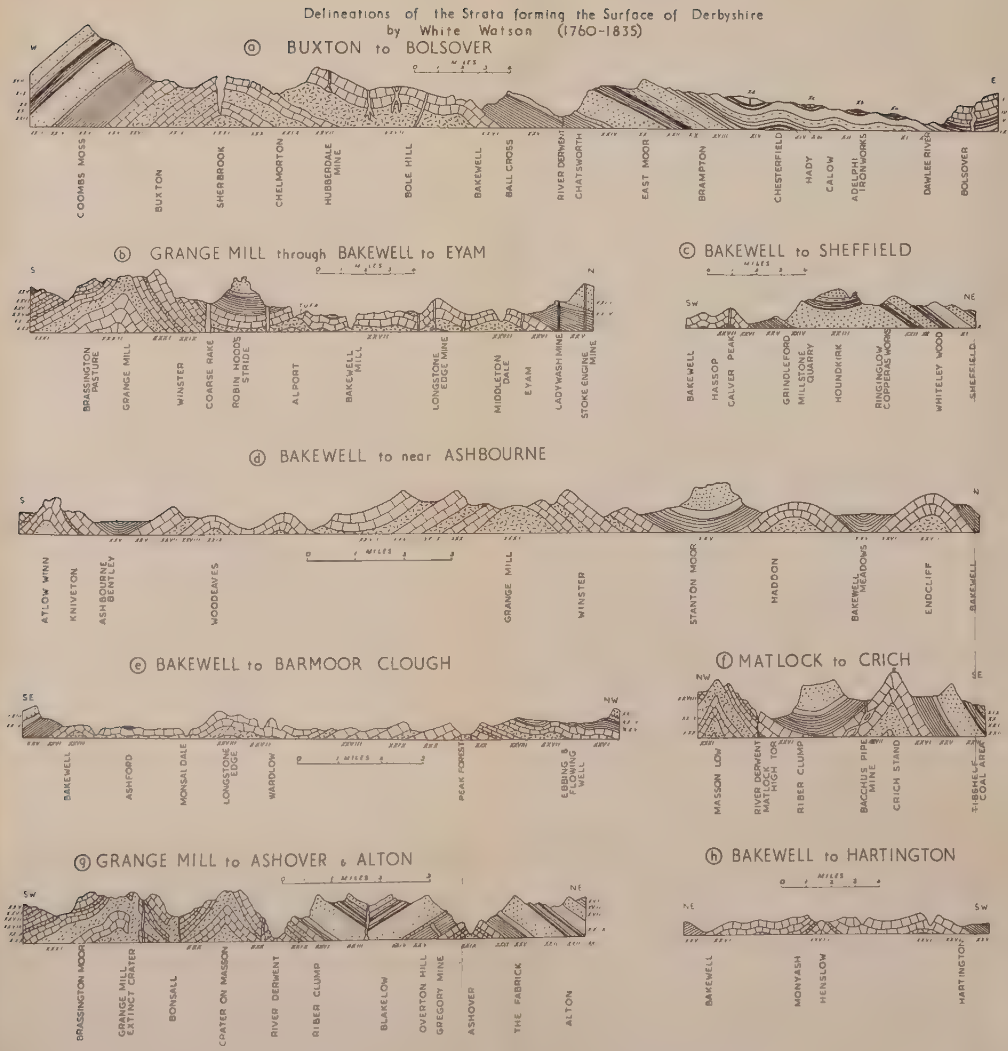
British Museum (Nat. Hist.) and Derby Museum. This section was not published until 1800. As there is no record of his having visited the area it is possible he prepared the section from mine plans, etc. It is less accurate than other sections but does show a crude resemblance to the structures depicted in Dunham & Stubblefields' map of the complex area around Greenhow Hill (1945). Watson there predicted the discovery of toadstones as in Derbyshire, but was proved wrong.

The first tablet giving a detailed cross-section of Derbyshire, as described in the *Delineation* (1811), was made in 1807 and given to the Duke of Devonshire on 20 February 1808. Several dozen were prepared during the next few years, on scales of half or one inch to a mile. Showing the structure from near Buxton to Bolsover (east of Chesterfield) this section compares favourably with more recent interpretations over much of its length but is less accurate at the two ends—the points farthest from Bakewell. Extra folds were introduced in the coalfield around Chesterfield. In this and all subsequent sections (Fig. 4) both thicknesses and dips are exaggerated.

Within a few years several other sections were prepared along different lines in Derbyshire (dates given are when the section is first known to have been drawn, although existing copies may bear later dates and incorporate amendments):

(i) from Alton through Ashover and Matlock to near Grange Mill (1813)
(ii) from Bakewell to Barmoor Clough, near Chapel-en-le-Frith (before 1825)
(iii) from Bakewell to near Ashbourne (probably before 1831)
(iv) from Bakewell to Sheffield (*c*. 1824)
(v) from Eyam Edge to Grange Mill (1813)
(vi) from Bakewell to Hartington (1821)
(vii) from Masson Low, near Matlock, through Crich to the Tibshelf Coal area (*c*. 1824)
(viii) through the Barlborough area (east of Chesterfield) (*c*. 1813 ?)
(ix) through the Kniveton inlier to beyond Ashbourne (probably 1820s)
(x) from Hazzlebadge pasture through Tideswell to Millers Dale (probably 1820s)

Also prepared were a number of more local sections through Mam Tor, Ecton Hill, Black Rock Corner near Ashford, Crich Stand, Longstone Edge, coal and ironstone strata near Chesterfield and several unspecified cliffs with detailed stratigraphy or the relationships of different types of mineral vein portrayed (see Derby C.B.C., MS. 8371). A number of tablets were made of simple columnar sequences of strata, comparative blocks of limestone or marble from various places, or illustrating geological principles. One, dated 1809, showed Derbyshire toadstones, lava from Vesuvius and Hecla, and Whinstones, inlaid as an erupting volcano between two lava scarps—'to show their affinity with one another'. With this he put an illustrative collection of 'the Productions of Furnaces and



KEY TO THE STRATA IN THE DELINEATION

I Crystallised Granular or Magnesian Limestone.
II Argillaceous Grit.
III Rock Coal.
IV Grit, shale, ironstone and clay.
V Rock Coal.
VI Shale with Ironstone.
VII Rock Coal.
VIII Culmous Grit.
IX Coarse Grit.
X Ferruginous Grit.
Xa, Xb, Xc, Xd Ironstone and Coal Basins.
XI Whetstone Grit.
XII Arenaceous Grit.
XIII Compact Grit, Cank.
XIV Fibrous Rock Coal.
XV Organic Grit.
XVI Friable Grit.
XVII Bituminous Shale and Coal.
XVIII Grindstone Sandstone.
XIX Fatiscent Grit.
XX Rock Coal.
XXI Clay, Coal Bind.
XXII Shelly Rock Coal.
XXIII Millstone Sandstone.
XXIV Shale Grit.
XXV Aluminous Shale.
XXVI Shell Limestone.
XXVII Basaltic Amygdaloid.
XXVIII Scaly Limestone and Dolomite.
XXIX Basaltic Amygdaloid.
XXX Compact Sugar-Limestone.
XXXI Basalt.
XXXII Compact Limestone. (Not included in some editions.)

Fig. 4. Reproductions of the more important detailed sections of Derbyshire Strata by White Watson. Key, taken from the *Delineation*, above. Modern conventional symbols have been used for limestone, toadstone, etc., as the originals vary from fine engraved print to hand-coloured manuscript. Sources: (a) White Watson, 1811; (g) White Watson, 1813; (b)–(f) and (h) Derby C.B.C. MS. 8371.

[*To face p.* 356

Chemical Laboratories to show by ocular demonstration and chemical facts that these substances are all the effect of one universal and common cause —heat!'

These sections show an intimate knowledge of Derbyshire stratigraphy and structure in spite of their inaccuracies, indeed they would do credit to many modern publications. The more important sections have been redrawn as Fig. 4. Together they could be used to construct a reasonable geological map of Derbyshire, but the only map of White Watson's seen by the writer is a crude thumbnail sketch reproduced here as Plate 10. This does bring out the anticlinal nature of the limestone area, unlike Farey's map (1811) which failed to recognise this simple fact. Farey also introduced a complex system of faults along the limestone–shale boundary but Watson clearly understood the more or less conformable nature of the boundary:

> 'In mining, this stratum [Shale] is generally a cover for veins of Ore in the Limestone beneath' (*Delineation*, 1811, 32). 'Owing to the undulating surface of the Shell Limestone the Basset of the Shale frequently extends a considerable way in the concavities of the Limestone before it feathers out' (*Delineation*, 1811, 37).

(see also Conybeare & Phillips, 1822, 454). Farey called on Watson several times and probably learnt a lot from him, in spite of which Farey complained (Farey, 1812, 27) of having been anticipated in publication. They evidently disagreed about several things, Farey at times apparently trying to find examples of theoretical concepts learnt elsewhere, and Watson observing, recording, and sometimes, deducing. White Watson's *Section of Strata in the Vicinity of Matlock Bath* (1813) was largely directed against Farey's concept of mountains being raised by satellite attraction from above, and he used Masson Hill and Grange Mill vents as evidence of 'Conical Hills' being raised by volcanic pressure from below. Whatever their differences, their discussions were doubtless of mutual benefit, and one wonders to what extent it is significant that Watson produced his first detailed section immediately after Farey's first season in Derbyshire.

White Watson drew, probably about 1825, an unusual stratigraphical diagram (Plate 9) in which the Derbyshire Limestone, toadstone, shale and gritstone succession is represented by a series of concentric circles, the oldest stratum being in the centre and the youngest outermost. This is bounded by an irregular line to represent the topography, with localities marked radially and indentations to varying depths to show the sections exposed in the various dales. Incomplete radial lines indicate the sections cut through in lead mine shafts. Although vaguely resembling Strachey's spiral section of the Somerset Coalfield (1719) it was probably evolved independently, indeed it has more in common with present-day 'ribbon sections'. In both this and some of his sections across Derbyshire Watson had difficulty with varying thicknesses of strata. He fully realised the beds did vary and usually managed to show this graphically, but in the circular diagram thickness figures were inserted at appropriate places without graphical variation.

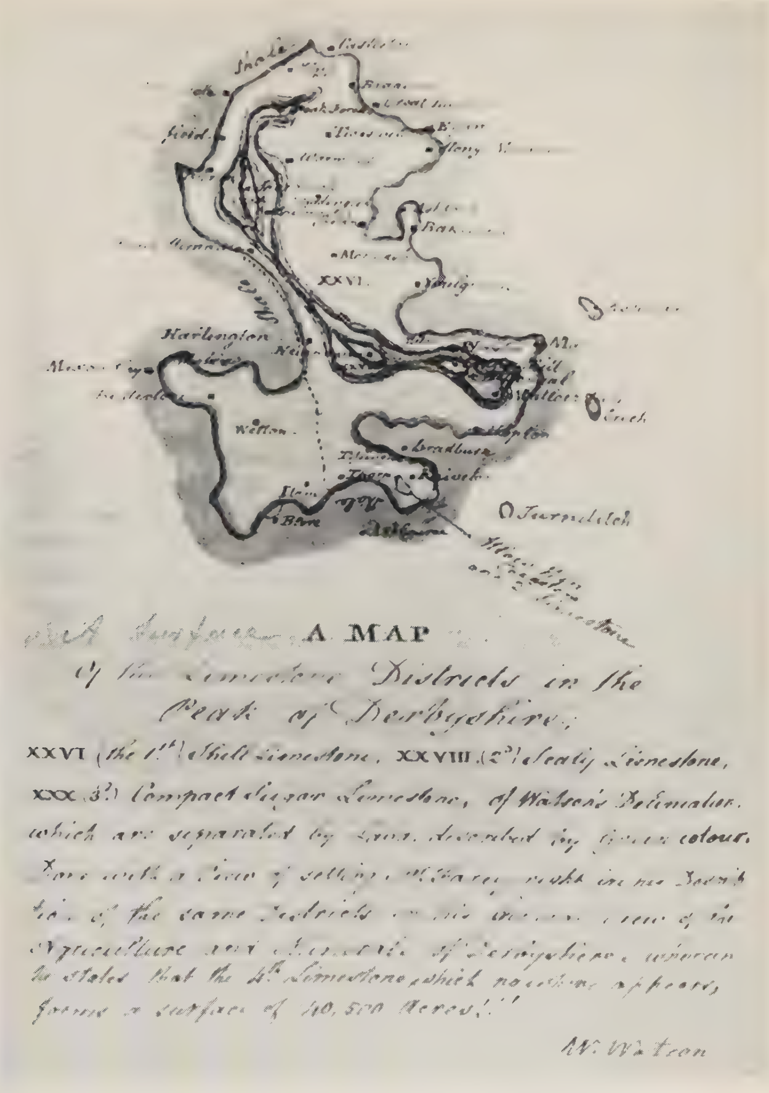
Watson was aware of Werner's ideas at an early date (see MS. 1, Vol. 3 below, 1800) and included a synopsis in the *Delineation* (1811, i), but among his manuscripts are some more detailed discussions and some draft sketches for Tablets based on these. The writer has not seen examples of any of these Tablets but the sketches include some interesting concepts. They include 'A Section through the Globe', 'Primitive Rocks', 'A Primary Mountain', 'Derbyshire Mines' and 'The British Strata'. The first of these is reproduced as Plate 11 and shows mountains of vertical Primary Rocks associated with intervening collapses of the Earth's crust, with synclinally disposed Secondary Rocks in the hollows, and anticlinally disposed Ternary Rocks in the core of the synclines! Werner made his Ternary Rocks horizontal but apparently Watson had to bend them to account for the curvature of the Earth's surface.

Watson also followed Werner in accounting for the formation of mineral veins by infilling from above in a note and drawing dated *c.* 1800, but later (1827) regarded mineral matter as having been forced in by uprising lava. Werner's classification of stratified rocks formed the basis of the organisation of most of Watson's collections.

Among White Watson's manuscripts are some of the original drawings for plates in Martin's *Petrificata Derbiensia* (Martin, 1809). Watson attempted to raise a subscription for such a work as early as 1790. At first unsuccessful, he was joined by Martin soon after, and subscriptions for a work to be produced by instalments were collected. Both Watson, and later Martin and Watson, distributed advertising leaflets. Martin went ahead in 1793, publishing instalments under his own name alone but using Watson's material and, in some cases, drawings but giving him little credit. They evidently fell out over this and in 1809 Martin republished the series alone as Volume I of *Petrificata Derbiensia*, in which Watson was not even mentioned. Martin died shortly afterwards.

Watson made many notes on miscellaneous topics, a few of which seem worthy of comment. He discussed the reasons why building stone should be laid 'in the bed' and recommended treatment with linseed oil to prolong its life. He knew that fungi would attack the bituminous black marble 'in damp churches'. He commented on a specimen of 'schist with the imperfect impression of a shell, apparently an areite, from the top of Snowdon, from which one would lay that Snowdon is not composed of primitive rocks' (dated *c.* 1820).

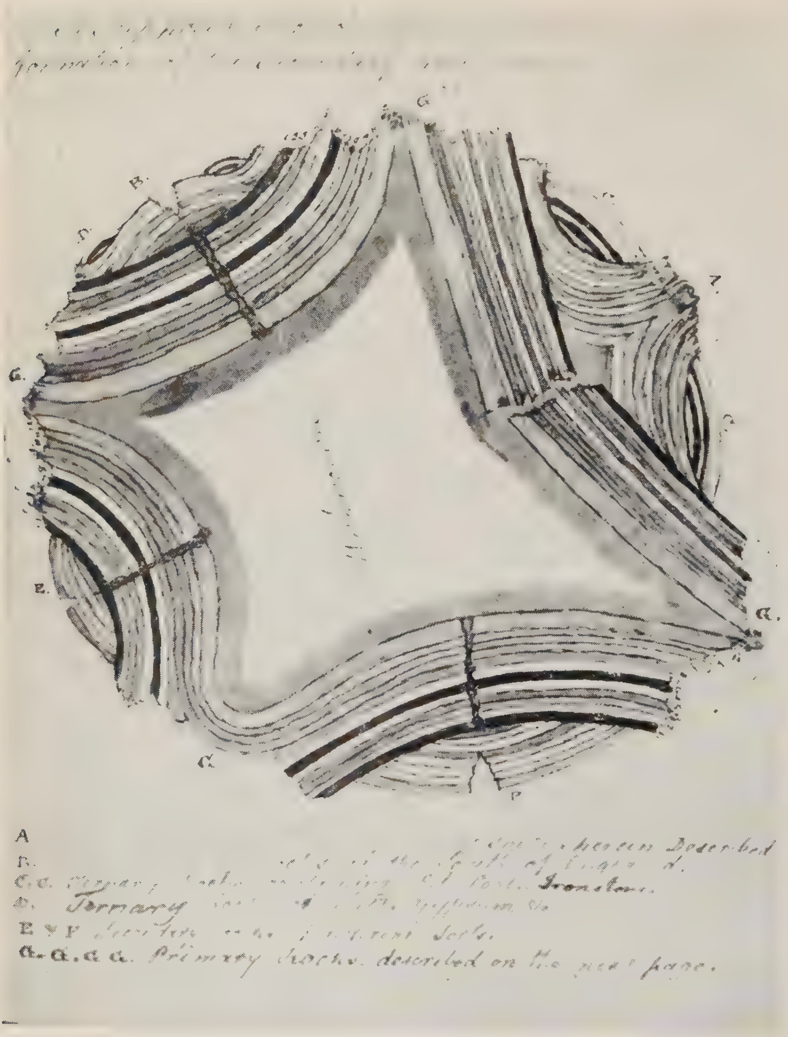
On the other hand he had peculiar ideas on some phenomena. Gritstone screes, so common in Derbyshire, resulted from being 'shook off by convulsions'. He made a subtle distinction between rock-coal and pit-coal.



[illegible] A MAP
of the Limestone Districts in the
Peak of Derbyshire;
XXVI (the 1st) Shell Limestone, XXVIII (2d) Scaly Limestone,
XXX (3d) Compact Sugar Limestone, of Watson's Delineation.
which are separated by Toads. described by Green colour.
x Done with a View of setting Mr Farey right in his Descrip-
tion of the same Districts in his General View of the
Agriculture and Minerals of Derbyshire, wherein
he stated that the 4th Limestone which nowhere appears,
forms a surface of 40,500 Acres!"

W. Watson

White Watson's manuscript 'Map of the Limestone Districts in the Peak of Derbyshire'. Date probably early 1820s. Key on Fig. 4. Original in Derby C.B.C. MS. 8371



White Watson's 'Supposed Section of the Globe after Formation of the Secondary and Ternary Rocks'. *c.* 1825. (The original has 'Ternary' in the title altered in pencil to 'Tertiary' by some unknown hand.) Original in Derby C.B.C. M.S. 8371

The former was found interbedded but the latter was of later formation and only found in the undulations of the gritstones. From his Buxton–Bolsover section it appears that he considered coals in the Millstone Grit Series and Lower Coal Measures as rock-coal, whilst those in the Middle Coal Measures were pit-coal, apparently formed from local swamps between 'conical hills' of gritstone (1811, 6). The pit-coal beds are not shown to dip beneath the magnesian limestone although placed in their correct position in his sequence of strata. He was a firm believer in toads being found alive inside rocks and dying on release by quarrymen, and he drew up an account of several supposed instances, probably with the intention of publishing it.

Watson's last few publications were of a more scientific nature. Printed as single pages they were either sold separately or added as extra pages to the *Delineation* (1811). The last publication, *Observations on Prismatic Gritstone* (1833), noted the nature of cooling cracks in heated rocks and compared them with joints in lavas, etc., although he went too far in assuming that crystal boundaries necessarily formed in a similar way.

5. INFLUENCE ON CONTEMPORARY GEOLOGICAL THOUGHT

White Watson had acute powers of observation and, at times, deduction but his writings contain relatively little discussion of theoretical concepts until his last few years. They are, for the most part, lithological descriptions. However, it is clear that he was willing to discuss ideas verbally in the form of lectures on geology and mineralogy delivered in his museum with the aid of illustrative material from his collections. Therein lies his contribution to geology—the collection of local material and information and the will to use it to demonstrate geological principles to all and sundry. He was at the same time a populariser of geological theory in terms of the clearly visible, and one who brought local facts to the notice of the theorists. Among his more notable callers were Farey, Buckland (who bought Tablets for the Oxford University Museum in 1822), W. Phillips (of Conybeare & Phillips, 1822), Professor Sedgwick (who paid five shillings to see the museum), Sir Joseph Banks, Erasmus Darwin (who bought a collection of fossils), J. Sowerby (who also bought fossils), and Bateman the archaeologist. Brongniart sent from Paris for 'more specimens' in 1791. Most of his notable visitors bought collections of fossils or minerals, Tablets or Delineations, and no doubt in many cases their conversations were of mutual benefit. Watson must have been an indefatigable collector to have been able to supply collections of 500 specimens sufficiently often to have printed catalogues to go with them. One wonders how many type specimens originated in these—and how many are incorrectly localised so that others could not trespass on White Watson's collecting grounds!

White Watson must go down as a pioneer in Derbyshire stratigraphy even if much of his work was hidden in manuscripts or inlaid in forgotten marble Tablets.

6. CONCLUSION

At his death in 1835, White Watson's collections were broken up and sold by auction. Bateman, the noted Derbyshire antiquarian, bought many manuscripts which subsequently went into Sheffield Public Library. Others came into the hands of Bingham, a Bakewell auctioneer, and eventually reached Derby Library. Others remained in private hands. Of his main fossil and mineral collection the fate is uncertain. Some of it was sold in the original cabinets to Hassop Hall, but was sold again later. Some was made into a rockery, which is reputed to have been barrelled up and sent to the British Museum in 1914 (Sherborn, 1940), although it could not be traced at a recent inquiry. Some polished slabs came into Milne's hands at the Ashford Marble Mill and may have been included in those Milne submitted in vain for the rebuilding of the House of Commons in 1844. In short, a lifetime's collection of some thousands of specimens was dispersed to the four winds! Of the hundred or so Tablets only fourteen have been traced by the writer.

ACKNOWLEDGMENTS

During the course of the work the writer found that Mr. J. M. Edmonds of Oxford University was also engaged in a similar study and his co-operation is gratefully acknowledged. The writer also wishes to thank Miss N. Kirkham, Messrs. E. Bradbury, R. Thornhill, G. Wooliscroft, Dr. F. J. North, the officials of the Buxton, Derby, Leicester, Manchester and Sheffield Museums and Libraries for their help, and also the Keeper of Collections in Chatsworth House.

REFERENCES

Axon, W. A. E. 1879. Notes on Lord Denman's Visit to Derbyshire in 1798. *Reliquary*, **19**, 255–6.

Bell, W. R. (editor). 1889. Observations on Bakewell by White Watson. *Derbyshire Archaeological Journal*, **11**, 157–73.

Challinor, J. 1947. From Whitehurst's 'Inquiry' to Farey's 'Derbyshire', a chapter in the history of English Geology. *Trans. N. Staffs. Fld. Cl.*, **81**, 52–88.

Conybeare, W. D. & W. Phillips. 1822. *Outlines of the Geology of England and Wales.* Part 1. lxi and 470. London.

Dunham, K. C. & C. J. Stubblefield. 1945. The Stratigraphy . . . of Greenhow Hill, Yorkshire. *Quart. J. geol. Soc. Lond.*, **100**, 209.

Edwards, W. N. 1931. *Guide to an Exhibition illustrating the early history of Palaeontology.* British Museum (Natural History). pp. 68. London.

Farey, J. 1811. *A General View of the Agriculture and Minerals of Derbyshire.* **1.** London.

———. 1812. An Account of the Great Derbyshire Denudation. *Phil. Mag.* (Tilloch's), **39**, 26–35, 93.

Ford, T. D. 1958. The Black Marble of Ashford-in-the-Water, Derbyshire. *Liverpool & Manchester Geological Journal*, **2**, 44–59.

Green, A. H. *et al.* 1869. Geology of the Carboniferous Limestone of North Derbyshire. *Mem. geol. Surv. U.K.*

Hunter, J. *c.* 1804. *Collectiana Hunteriana.* **6.** B.M. Addt. MSS. 24440/18.

Martin, W. 1809. *Petrificata Derbiensia.* **1.** Wigan.

Mawe, J. 1802. *The Mineralogy of Derbyshire.* xv and 211. London.

Sherborn, C. D. 1940. *Where is the . . . collection?* pp. 150. Cambridge.

Strachey, J. 1719. Observations on the Somerset Coalfield. *Phil. Trans.*, **30**, 968.

Whitehurst, J. 1778. *An Inquiry into the Original State and Formation of the Earth.* London. (2nd edition, 1786.)

APPENDIX I. WHEREABOUTS OF SURVIVING TABLETS

Chatsworth House, Derbyshire:

- 2 tablets of Derbyshire 'Fossils' (actually comparative slabs of rocks and minerals inlaid together). One dated 1788.
- 1 tablet of eighteen varieties of Toadstone. Undated, but probably of same date as above.

Manchester Museum:

- 1 tablet of the Strata of Derbyshire as in the *Delineation* (1811) inscribed 1822.

Derby Museum:

- 1 tablet of the Strata at Ecton Hill, Staffs. *c.* 1797.
- 1 tablet of a Mountain in Derbyshire, *c.* 1791.
- 1 tablet of the Strata in Bewerly Liberty, Yorks, *c.* 1797.

British Museum (Natural History):

- 1 tablet of a mountain in Derbyshire, with a Section of the Strata of Ecton Hill on the back. 1794.
- 1 tablet of the Strata in Bewerly Liberty, *c.* 1797.

Oxford University Museum:

- 1 tablet of Limestones (comparative slabs) dated 1821.
- 1 tablet of the Strata of Derbyshire from Buxton to Bolsover as in the *Delineation*, inscribed 1822.
- 1 tablet of the Strata of Derbyshire from Alton to Grange Mill, inscribed 1822.

Leicester Museum:

- 1 tablet of Toadstones, Lavas and Whinstones, 1809.

One other, as the *Delineation* (1811), in private hands.

APPENDIX II. PUBLICATIONS

1788 *An explanation of a Table representing the Strata in Derbyshire.* pp. 16. Sheffield. 16°. (D.C.B.C. 3793.)

1790 *Prospectus of a Catalogue and Description of Derbyshire Fossils.* One page. Sheffield. (S.C.L.560.94251S.)

c. 1791 as last with William Martin as co-author.

1791 *An explanation of a Tablet representing a section of the strata of Derbyshire.* 2nd Edn. pp. 16. Sheffield. 16°. (D.C.B.C. 3793, B.M. B260(19).)

1794 as last, reprinted in Bakewell. (D.C.B.C.3793 and B.M. B260(19).)

1797 as last, revised and enlarged. pp. 26. Bakewell. 12°. (D.C.B.C. 3793 and B.M. T2042(2).)

1797 as last, reprinted in 8°. (B.M.(N.H.)P.Misc. 86).)

1800 *An explanation of a Tablet representing a Section of the Strata of Bewerly Liberty, near Pateley Bridge, Yorkshire.* pp. 16. London. 16°. (Also marked Bakewell 1797.) 200 copies printed. (Linn. Soc. and D.C.B.C. 4416.)

1803 *A Catalogue of a Collection of Limestones* (mainly from Bewerly Liberty). pp. 23. London. 16°. (B.M. B260(23).)

1803 *A Catalogue of a Collection of Limestones* (mainly Derbyshire Magnesian Limestones). pp. 23. Bakewell. 16°. (D.C.B.C. 4416.)

1805 *A Catalogue of a Collection of Limestones* (mainly Bewerly Liberty). Sheffield. 8°. (B.M. B376(6); G.S.P.Misc. 148; D.C.B.C. 4477.)

1805 *A Catalogue of a Collection of Limestones* (mainly Derbyshire). Derby. 8°. (B.M. B392(2).)

1805 *A Catalogue of a Collection of Fossils.* Dublin. 8° (G.S.P. Misc.39). (Another copy has a *Catalogue of a Collection of Fossils from the Hartz Mountains*, said to be translated from the German by W. W.) (B.M. 1255c).

1811 *A Delineation of a Section of the Strata in Derbyshire.* pp. viii and 76. Sheffield. 4°. 500 copies printed. (B.M. B348(12); D.C.B.C. 8371; D.C.L.; S.C.L., etc., etc.)

1812 Poems intended to accompany (1811) above. Bakewell. 4°. 200 printed. (B.M. B348(12); D.C.B.C. 8371, etc.)

1813 *A Section of the Strata in the vicinity of Matlock Bath, from Ashover to Bonsall . . . to correct Farey's Section.* pp. vi and 19. Chesterfield. 4°. Fifty copies printed. (Ches.P.L.; S.C.L. 560.94251S.)

1826 *On Entrochal Marble.* One page. Bakewell. 100 printed. (D.C.B.C. 8371; S.C.L. 560.94251S.)

1827 *A Theory on the Formation of Mineral Veins.* One page. Bakewell. (D.C.B.C. 8371; S.C.L. 560.94251S.)

1829 *A Description of Slickensides.* Bakewell. 100 printed. One page. (D.C.B.C. 8371; S.C.L. 560.94251S.)

1833 *Observations on prismatic gritstone.* One page. Bakewell. (D.C.B.C. 8371; S.C.L. 560.94251S.)

NOTES: The last four above were frequently bound in the back of the 1811 *Delineation*, many copies of which are still scattered about libraries or in private hands.

Initials and figures in brackets are references to copies examined: D.C.B.C. = Derby County Borough Council Library; D.C.L. = Derbyshire County Library; G.S. = Geological Society Library; B.M. = British Museum Library; S.C.L. = Sheffield Central Library; Ches.P.L. = Chesterfield Public Library; Linn. Soc. = Linnean Society Library; B.M.(N.H.) = British Museum (Natural History) Library.

APPENDIX III. MANUSCRIPTS

A number of White Watson's diaries, notebooks, account books and other personal documents have survived and have been invaluable in building up a picture of his daily life and geological outlook. The manuscripts include:

(1) His MS. catalogue of his personal collection (now in the Bagshaw MSS. in Sheffield Central Library, nos. 316/1–3) in three volumes.

Vol. 1, dated 1799, refers to the collection having been started in 1774, and contains items almost all from Derbyshire numbered 1–1001 (1–364 rocks and minerals; 370–526 fossils; 527–563 marbles; 564–650 vein formations; 650–1001 miscellaneous). A few items carry references to Martin's plates (1809).

Vol. 2, dated 1803–6, is a catalogue of fossils arranged according to their respective strata, but includes many minerals as 'products' characteristic of certain strata in Derbyshire.

Vol. 3, dated 1800, is a 'catalogue of a systematic collection of fossils arranged according to Mr. Werner's system'. Although forming a unified collection it is far from being restricted to Derbyshire, or even Britain, and may have been obtained complete possibly from Freiburg.

(2) His personal copy of the *Delineation* (1811) (now in Derby C.B.C. Library, MS. no. 8371). The printed book was only 76 pages long but this is a volume of some 200 pages, and includes bound in copies of all his later publications with many MS. corrections to the text, also a miscellany of notes, sketches, diagrams for Sections of Strata never published, some of the plates from Martin's *Petrificata Derbiensia* (1809) and some original drawings (some signed by Martin and others by Watson). The whole volume probably constituted his personal reference book for use during his lectures and discussions.

(3) His pocket diaries bound into six volumes by T. Bateman (now in the Bagshaw MSS. in Sheffield Reference Library, nos. 317/1–6). The diaries range from 1780 to 1831, but they are not in order and only about half the years are represented. In some cases a diary contains entries for several years. They are not day-to-day records of his doings, merely jottings about geology, the weather, his garden and other memoranda.

(4) His Cash Book, a bound ledger with a continuous record of cash in and out from 5 July 1796 to 28 March 1833. (Now in private hands.) If the entries are really a complete record of his income and expenditure he was often close to bankruptcy!

(5) A letter giving his opinion on the sulphate of barytes discovered near Arborlow, Middleton-by-Youlgreave, on 6 August 1833. (Now bound into Martin (1809) in Sheffield Central Library.)

(6) His MS. catalogue of a collection of fossils, pp. 107, dated 1799. (Now in B.M.(N.H.) Mineralogy Dept.)

(7) His album of silhouettes, dated 1806. (Now in Derby C.B.C. Library.) These were inked silhouettes of local worthies or important visitors, from which either paper cut-outs or inlaid marble silhouettes were prepared.

(8) An early MS. catalogue of his collections entitled 'An Explanation of a Table . . . etc. . . . this book is the mineralogy of Derbyshire, 1788–   '. The items are not in numerical order and a note says 'transferred to larger volumes in 1802'. (Now in private hands.) This contains many sketches of specimens which do not reappear in any of the larger MS. catalogues mentioned above.

(9) A collection of White Watson's letters to W. Bateman from 1821 to 1835. (Now in Oxford University Museum Library.)

(10) An MS. catalogue of a collection of Fossils, the produce of Derbyshire, arranged according to their respective strata, by a Tablet representing the same strata. Dated 1794. 148 specimens listed in 16 pages. (Now in Derby C.B.C. Library, no. 9040.)

Extracts from some of these diaries and possibly other documents not seen by the author, edited by Bell, appeared in the *Derbyshire Archaeological Journal* for 1889. The extracts refer almost entirely to Bakewell history.

The Gault–Lower Greensand Junction and the Lower Gault of the Maidstone By-Pass (East Section), Kent

by H. G. OWEN

Received 25 February 1959

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ABSTRACT: The Gault–Lower Greensand Junction and the Lower Gault exposed in temporary sections cut during the construction of the Maidstone By-Pass (East Section) in north Kent are described. From field evidence it is confirmed that the apparent gap in the Lower Gault sequence in the Maidstone–Bearsted area reported by Spath and H. J. W. Brown does not exist. The phosphatic nodule beds of the Gault–Lower Greensand Junction classified with the *mammillatum* and basal *dentatus* Zones are overlain by about twenty-six feet of clays belonging to the Lower Gault. The *dentatus-spathi*, *intermedius*, *niobe*, and *subdelaruei* Subzones are present in ascending order. There follows the *meandrinus* Subzone, a name proposed for the upper nodule bed of Bed IV and the base of Bed V at Folkestone and their lateral equivalents. The *lautus-nitidus* Subzone and a thin representative of the *daviesi* Subzone follow, underlying a bed of phosphatic nodules belonging to the *cristatum* Subzone. A comparison is made with the sections at Folkestone and Greatness and certain depositional features in the Lower Gault are discussed.

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1. INTRODUCTION

THE RECENT construction of the East Section of the Maidstone By-Pass motorway in the Maidstone–Hollingbourne area of northern Kent has exposed sections in the Folkestone Beds and Gault providing new and important information about them. The principal cuttings along its route exposed the Folkestone Beds and the Upper Gault, but at the localities listed below the Gault–Lower Greensand Junction and the Lower Gault were visible.

The stratigraphy of the Gault–Lower Greensand Junction and the Gault in this area has been described on the basis of sections formerly exposed at Eyhorne Street, Hollingbourne (Jukes-Browne, 1900, 85; H. J. W. Brown, 1930, 113), and at Bearsted (Spath, 1926, 422; H. J. W. Brown, 1930, 113). Spath (1926, 1943) and Brown (1930) considered that there was a marked non-sequence in the Lower Gault at these localities and that this included all horizons between the *dentatus-spathi* and *cristatum* Subzones (Brown, 1930, 113; Spath, 1943, 738). In the *Summary of Progress for 1957* (1958, 48), however, it was stated that Dr. Casey from a re-examination of relevant material had concluded that no gap exists in the Lower Gault sequence in mid-Kent.

Through the courtesy of Kent County Council and Messrs. Richard Costain Limited, the author was permitted to examine the sections exposed during the construction of the East Section of the Maidstone By-Pass. It can now be confirmed from field evidence that although the Lower Gault is thinner than at Folkestone or in the Trottiscliffe–Sevenoaks area, the subzonal sequence is complete.

2. LOCATION OF SECTIONS

The East Section of the Maidstone By-Pass extends from the A.20 road near the Old England public house, west of Eyhorne Street, Hollingbourne, westwards to Farthings about one mile north of Maidstone. Sections in the Gault–Lower Greensand Junction and Lower Gault were exposed at the following localities.

Section 1. Chrismill Lane Subway and Bridge. The Gault–Lower Greensand Junction and basal Lower Gault were exposed on the north and south sides of the Maidstone–Ashford railway line in trenches made for the supports of the Chrismill Bridge. Section 1a was situated thirty feet north of the railway line, about 230 yards westwards from Woodcut Cottages, and about 125 yards east of the old Chrismill Lane Bridge (81705555)[1]. The Lower Gault was exposed in the cutting for the Chrismill Lane Subway about sixty yards north-west of Section 1a.

Section 2. Drainage man-hole, Longham Wood Cutting (81255595). On the south-west side of this deep cutting in the *orbignyi* and *varicosum* Subzones of the Upper Gault, a drainage man-hole and adjacent trenches exposed the upper part of the Lower Gault. It is situated about 725 yards north-east of the Barty House and 525 yards north-westwards from Chrismill Lane.

Section 3. Water Lane Bridge (80855630). The upper part of the Lower Gault was exposed in a cutting made on the south-east side of Water Lane about 500 yards NNE. of the railway bridge carrying the Maidstone–Ashford railway line over Water Lane and 575 yards north-westwards from Section 2.

Section 4. A.249 Clover Leaf. The Gault–Lower Greensand Junction and the Lower Gault were exposed in the north-west quadrant of this Clover Leaf and in the track of the By-Pass near the junction with the south-east quadrant. The cutting for the north-west quadrant (77805745) exposed a complete, but faulted and steeply dipping section extending from the Folkestone Beds to the base of the Upper Gault; the edge of the Gault outcrop being located 585 yards north-east of the Chiltern Hundreds public house, at the south-east end of Kiln Wood. The section in the floor of the By-Pass commenced at about 175 yards east of the southern end of the bridge carrying the A.249 over the By-Pass, the edge of the Gault outcrop being located farther south than recorded on the Geological Survey map (Sheet 288). The writer could find no evidence to support the presence of a subsidiary fault extending from the southern end of Park Wood into Horrish Wood (Casey, 1959). The sections in the floor of the By-Pass and in adjacent trenches indicate a structure closely similar to that shown on the Geological Survey one-inch-to-the-mile Sheet 288, the cross-section of which cuts the Gault outcrop about half a mile ESE. of the Clover Leaf.

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[1] All Grid References lie within the 100 km. square (TQ).

Section 5. Grange Lane Cutting. At the north-west end of the Grange Lane cutting, about 500 yards SSE. from Boxley Abbey near the point where the original route of Grange Lane traverses the By-Pass, clays of the Lower Gault were seen to be faulted against the Folkestone Beds, and in the fault-zone, patches of highly disturbed Gault–Lower Greensand Junction beds were seen (76305825).

The By-Pass between the Grange Lane cutting and the Yew Tree Inn, Farthings, is built up into an embankment. In the bank running parallel to the old Grange Lane and fifty feet from it, and in ditches on the north-east side of the By-Pass parallel to the new Grange Lane, the *cristatum* nodule bed at the top of the Lower Gault was seen.

Section 6. Boarley Bridge (757586). On the east side of the Sandling–Boarley road a few yards north of the Yew Tree Inn, Farthings, the trench for the supports of the bridge exposed a few feet of Lower Gault underlying a thick capping of river deposits.

3. STRATIGRAPHY

(a) Gault–Lower Greensand Junction

(*i*) *Description of Sections.*

Section 1a. The section at Chrismill showed the following sequence:

Bed No.	Lithology	ft.	in.
Division A (Lower Gault)	Bed of phosphatic nodules, mainly casts of species of *Hoplites*, in glauconitic clay		3–4
15	Glauconitic silt		4
14	Line of spherical blackish septarian phosphatic nodules in glauconitic silt		2
13	Glauconitic loam with wisps of grey clay, becoming a silt towards the top	1	4

Bed No.	Lithology	ft.	in.
12	Line of spherical blackish septarian phosphatic nodules in glauconitic loam		2
11	Glauconitic brownish loam		3
10	Dense band of large gritty phosphatic nodules cemented by carstone		4
9	Glauconitic brownish loam		2
8	Carstone seam cementing a line of gritty phosphatic nodules		2
7	Streaked brown glauconitic sand with occasional partly phosphatised fossils		4
6	Band of greyish phosphatic nodules in greyish glauconitic sand		4
5	(ii) Grey sand with thin streaks of ferruginous sand, with at the base, ...		4
	(i) a persistent line of soft, white sandy phosphatic nodules in grey sand, at the junction with bed 4, or included in its irregular top		2
4	Ferruginous ill-graded sand with wisps of grey clay increasing towards the top; scattered incipient phosphatic nodules	1	4
3	Passage bed with streaky seams of orange-brown sand alternating with grey pebbly sand; a few incipient phosphatic nodules ... ... about		8
2	Streaked ferruginous and glauconitic sand alternating with white sand ... ... about	1	2
1	Sharp white sand with wisps of glauconitic sand. Top of the Folkestone Beds. ... measured to		7

The streaked sands of Bed 4 are obviously of secondary formation.

Section 4. The section in the north-west quadrant of the A.249 Clover Leaf is as follows:

Bed No.	Lithology	ft.	in.
Division A (Lower Gault)	Blackish phosphatic nodules, mainly casts of species of *Hoplites* in a highly glauconitic clay with some crushed fossils		3
17	Glauconitic sandy clay becoming more sandy below		8
16	Line of spherical septarian phosphatic nodules ...		2
15	Glauconitic sand	1	3
14	Line of septarian phosphatic nodules in glauconitic sand		1
13	Glauconitic sand becoming more ferruginous, ill-graded, and less glauconitic downwards ...	1	2
12	Highly argillaceous glauconitic ill-graded loam with scattered small septarian phosphatic nodules		1
11	Glauconitic ill-graded loam becoming ferruginous downwards		4
10	Line of septarian phosphatic nodules in a matrix of bed 9 below		2
9	Ferruginous ill-graded loam		2

Bed No.	Lithology	ft.	in.
8	Line of large gritty phosphatic nodules in ferruginous grit		3
7	Coarse ill-graded ferruginous loam with occasional phosphatic nodules		3
6	Ill-graded grit with many scattered gritty phosphatic nodules		6
5	Ill-graded yellowish grit with wisps of light-grey clay		6
4	Line of gritty phosphatic nodules		1
3	Coarse pebbly yellow sand		8
2	Line of gritty phosphatic nodules in yellowish sand		1
1	Variegated brown and grey sand with seams of grey clay		3
	Uppermost Folkestone Beds.		

A closely comparable section was exposed on the track of the By-Pass near to the junction with the south-east quadrant of the Clover Leaf.

Section 5 in the Grange Lane cutting was not suitable for accurate measurements to be made. Diagrammatic vertical sections are given in Fig. 1.

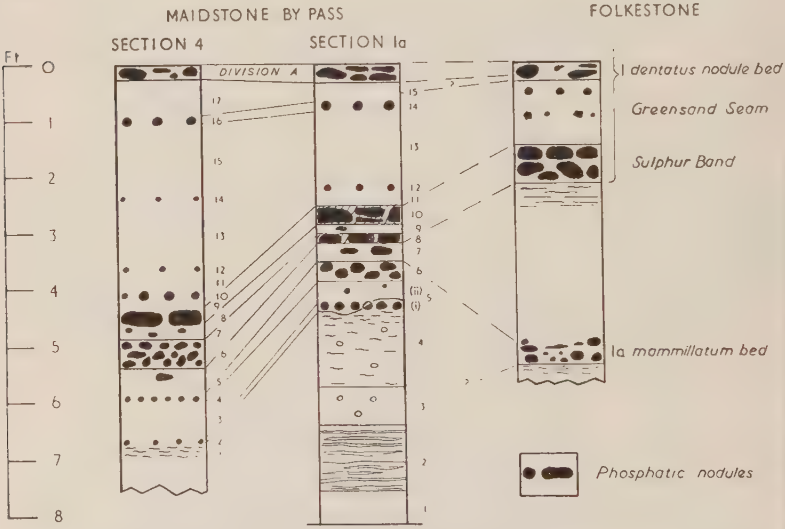

Fig. 1. Vertical sections of the Gault–Lower Greensand Junction Beds in the Maidstone By-Pass (East Section) and at Folkestone

(*ii*) *Classification.*

Section 1a. Beds 3–10 are classified with the *monile* Subzone *s.l.* The fossils include:

Bed 3 *Douvilleiceras* sp., four inches below top.

Bed 5 (i)	*Douvilleiceras mammillatum* (Schlotheim) Spath, *D.* aff. *orbignyi* Hyatt, *Protohoplites* aff. *latesulcatus* (Sinzov), *P.* spp., *Sonneratia* cf. *dutempleana* (d'Orbigny), *Inoceramus salomoni* d'Orbigny, *Barbatia marullensis* (d'Orbigny).
Bed 6	*D. mammillatum*, *Beudanticeras* aff. *ligatum* (Newton & Jukes-Browne) Spath, *Otohoplites* cf. *guersanti* (d'Orbigny), *O.* sp. ind.
Bed 7	*D. mammillatum*, *D. orbignyi* Hyatt, *Panopea gurgitis* var. *plicata* J. Sowerby.
Bed 8	*D.* aff. *mammillatum*, *Beudanticeras* aff. *ligatum* (Newton & Jukes-Browne) Spath, *Protohoplites* sp. *Otohoplites* sp., *Protanisoceras* sp.
Bed 10	*Otohoplites?* sp. ind.

No fossils were obtained from Beds 11–15, but they probably represent the *inaequinodum* and *benettianus* Subzones.

Section 4. The fossils include:

Bed 2	*D. orbignyi* Hyatt, *Barbatia marullensis* (d'Orbigny).
Bed 4	*D. mammillatum*, *D. orbignyi*, *Eutrephoceras clementinum* (d'Orbigny), *Inoceramus salomoni* d'Orbigny; Mr. R. Hodgkinson obtained a fragment of *Hamites praegibbosus* Spath, which probably came from this bed.
Bed 5	*Douvilleiceras* sp., *Otohoplites* sp.

From the fossils obtained, and a comparison of the lithology with Section 1a, beds 1–8 are classified with the *monile* Subzone *s.l.*, while beds 9–17 represent the *inaequinodum* and *benettianus* Subzones.

(b) Lower Gault

(*i*) *Description of Sections.* In the Lower Gault of the East Section of the Maidstone By-Pass four lithological divisions can be easily recognised, and are remarkably constant so far as it was possible to judge (Fig. 2).

Section 4. The cutting for the north-west quadrant of the A.249 Clover Leaf exposed a complete sequence through the Lower Gault. Two strike faults possessing small downthrows northwards caused marked changes in the angle of dip which is 25–30° towards the NNE.

Division	Lithology	ft.	in.
D	Bed of blackish phosphatic nodules in bluish-grey clay (*cristatum* nodule bed)		3–4
C	(iii) Bluish-grey clay with brownish partings and pockets of limonite after pyritised fossils, becoming darker upwards. Scattered line of small buff phosphatic nodules occurs 5 inches above the base ... ... about	4	0
	(ii) Seam of brown phosphatic nodules		1–2
	(i) Darkish rather fawn-grey shelly clay with scattered phosphatic nodules in the top 1 foot, passing down into light speckled fawn-blue-grey clay with sporadic lenticles of ferruginous marly clay and marlstone in the lower part	6	0

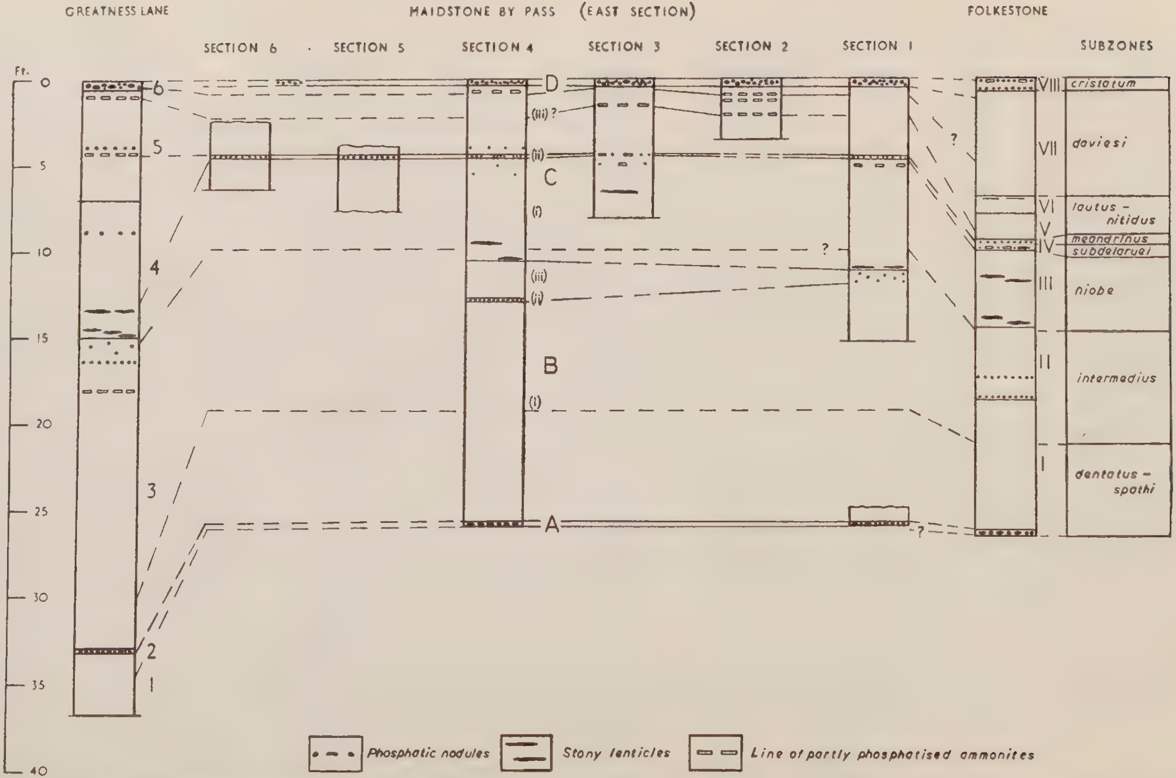

Fig. 2. Vertical sections of the Lower Gault at Greatness, Maidstone By-Pass (East Section) and Folkestone

Division	Lithology	ft.	in.
B	(iii) Dark blue-grey clay with shell seams, lightening in colour towards the top	2	2
	(ii) Seam of irregular-shaped phosphatic nodules		2
	(i) Grey slightly fawn clay with many shell seams, and bands of speckled clay at certain levels, passing down into 3 feet 3 inches of greenish-grey clay becoming progressively darker and more glauconitic downwards. The clays are blocky with yellowish partings and seams of incipient buff phosphatic nodules occur up to a height of 8 feet 8 inches above the base	13	0
A	Bed of blackish phosphatic nodules, some septarian, in a highly glauconitic clay with some crushed fossils		3–4

Section 3. The Water Lane Bridge section situated 3500 yards ESE. of the A.249 Clover Leaf exposed, in ascending order, the upper three feet seven inches of Division C(i), C(ii) one inch, and C(iii) three feet ten inches, and the *cristatum* nodule bed Division D (four to seven inches). Unfortunately, the lower beds of the Lower Gault were not exposed in this section which is about five-eighths of a mile towards the ENE. of the old Bearsted Brick and Tile Works pit (Brown, 1930), but the base of the Gault was located in the road bank on the east side of Water Lane about 425 yards SSW. of Section 3. The angle of dip is low, and towards the NNE.

Section 2. The man-hole excavation in the Longham Wood cutting and adjacent drainage trenches exposed the upper three feet of C(iii) and Division D (two to six inches). There is a tendency for Division D to divide a little, noted also in Section 4, but there is no question of there being two separate nodule beds.

Section 1. A composite section through the Lower Gault was exposed in the trench for a support of the Chrismill Bridge (Section 1a) and in the Chrismill Lane Subway (Section 1b). Division A (three to four inches) overlain by several feet of weathered glauconitic clay forming the lower part of B(i) was exposed in Section 1a. The upper three feet three inches of B(i) was exposed in Section 1b, overlain by nine inches of dark fawn-grey clay with scattered phosphatic nodules representing B(ii) and (iii). Divisions C and D are closely comparable in thickness and lithology with that described for Section 4. Slight rucking in the clays could be detected, but the dip 3–4° towards the NNE. is constant.

North-westwards from Section 4, the Lower Gault was imperfectly exposed. Section 5 in the Grange Lane cutting proved to be too disturbed to be measured with accuracy. In a man-hole at this locality, and in the side of the cutting, the bulk of C(i), the nodule bed C(ii) and about one foot of C(iii), were exposed dipping south-west but badly contorted and slickensided. At the easterly end of the section, the fault has been cut at such an angle that Folkestone Beds appear to override the Gault. Patches of C(iii) could be seen in areas free from river deposits in the floor of the By-Pass where the old Grange Lane traversed its track. Division D was located in the bank parallel to the old Grange Lane on the south-west side of the By-Pass which is here embanked, and in drainage trenches on the north side. At Boarley Bridge, Section 6 exposed two feet of Division C(i), the nodule bed C(ii) one inch, and two feet of C(iii), underlying a thick capping of river deposits.

Diagrammatic vertical sections are given in Fig. 2.

(*ii*) *Classification.*

Division A yielded the following ammonites:

> *Pictetia astieriana* (d'Orbigny), *Hamites rotundus ?* J. Sowerby, *Hamites* sp., *Hoplites dentatus* (J. Sowerby) and the varieties *robusta* Spath, *densicostata* Spath, and *sulcata* Seitz, *H.* aff. *persulcatus* Spath, *H. spathi* Breistroffer, *H. rudis* Parona and Bonarelli, *H. paronai* Spath, *H.* aff. *vectensis* Spath, *H.* cf. *pretethydis* Spath *H.* cf. *escragnollensis* var. *angustumbilicata* Seitz, *H.* aff. *latesulcatus* Spath, *H.* aff. *mirabilis* Parona & Bonarelli, *H.* spp., *Oxytropidoceras* aff. *roissyanum* (d'Orbigny).

In the overlying six feet five inches of clays forming the lower part of Division B(i) exposed in Section 4, seams of crushed *Inoceramus concentricus* Parkinson are common above a height of two feet eight inches from the base. The first appearance of *Anahoplites intermedius* Spath at a height of six feet five inches above Division A is taken to mark the base of the *intermedius* Subzone. Division A and the lower six feet five inches of B(i) are classified, therefore, with the *dentatus-spathi* Subzone.

Anahoplites intermedius Spath, *A. mantelli* Spath and *A. praecox* Spath occur in shell seams throughout the remaining six feet seven inches of Division B(i) in Section 4. The line of phosphatic nodules B(ii) yielded *A.* aff. *praecox* Spath, *A.* sp., and *Hoplites* cf. *dentatiformis* Spath. Crushed *Anahoplites* occur in B(iii) in shell seams but are not as common as in the beds beneath. At a height of about five inches above the base of Division C in Section 4, *Falciferella milbournei* Casey was obtained from shelly clay. The upper limit of the *intermedius* Subzone was not satisfactorily determined in Section 4 or in 1b, but it includes the upper part of Division B from a level six feet five inches above Division A, and the lower part of Division C(i).

The bulk of C(i) contains crushed *Anahoplites planus* (Mantell), *Dimorphoplites* cf. *niobe* Spath, *Euhoplites loricatus* Spath, *Hamites gibbosus* J. Sowerby, and numerous *Inoceramus concentricus* Parkinson, among other fossils, and is classified with the *niobe* Subzone.

The *subdelaruei* Subzone is represented in Sections 4 and 5 by a single one to two inch thick bed of phosphatic nodules in weathered clay, with fossils preserved as incomplete internal casts. In Sections 1b, 3, and 6, it could be seen that the fossils are mainly partly phosphatised, the remainder of the shell being crushed in the clay. Fossils include:

> *Hamites attenuatus* J. Sowerby, *H. rotundus* J. Sowerby, *H.* aff. *compressus* J. Sowerby, *H.* spp., *Euhoplites* aff. *microceras* Spath, *E.* aff. *aspasia* Spath, *E.* aff. *subtuberculatus* Spath, *E.* spp., *Anahoplites* aff. *splendens* (J. Sowerby), *A. planus* (Mantell) and the variety *sulcata* Spath, *A. pleurophorus* Spath, *Dimorphoplites* aff. *niobe* Spath, *D.* aff. *doris* Spath, *D.* cf. *pinax* Spath, *D.* aff. *biplicatus* (Mantell), *D.* spp., *Inoceramus concentricus* Parkinson, *I. anglicus* Woods, *Nucula* spp., *Notopocorystes stokesii* (Mantell), *Eucorystes broderipii* (Mantell), cf. *Hoploparia* sp.

Poorly preserved ammonites seen in the lower foot of Division C(iii) in Sections 3 and 4 indicate that these deposits belong to an horizon beneath the restricted *lautus* Zone (Owen, 1958). Section 2 in the Longham Wood cutting showed a less weathered sequence in which fossils were uncommon below a level one foot seven inches beneath the top of C(iii). At this level, *Euhoplites meandrinus* Spath was obtained, and one inch above it, species of *Euhoplites* occur indicating the *lautus-nitidus* Subzone. The clays of C(iii) up to a level one foot six inches beneath the *cristatum* nodule bed (Division D) are classified with the *meandrinus* Subzone, proposed here to include the upper nodule bed of Bed IV, and the basal few inches of Bed V beneath the restricted *lautus* Zone at Folkestone, and their lateral equivalents elsewhere.

In Section 2, the seam of crushed or poorly phosphatised ammonites which occurs at a depth of eighteen inches beneath Division D yielded *Euhoplites* of the *truncatus–opalinus* group. These all possess the typical clean-cut ventral channel characteristic of the *Euhoplites* of the strict *lautus* Zone. *Euhoplites opalinus* Spath was obtained at a depth of sixteen inches, and with *Euhoplites proboscideus* (J. Sowerby) in a shell seam eight inches below Division D. A shell seam four inches beneath Division D contains ammonites indicating the *daviesi* Subzone. Division C(iii) from a level eighteen inches beneath Division D up to a level four inches beneath it is, therefore, classified with the *lautus-nitidus* Subzone.

The shell seam at a depth of four inches below D yielded partly phosphatised *Anahoplites daviesi* Spath and the variety *ornata* Spath, together with *A. planus* (Mantell). The upper four inches of C(iii) yielded *A. planus* var. *gracilis* Spath at a depth of two inches, and *Euhoplites opalinus* and *Dimorphoplites biplicatus* (Mantell) from a depth of one inch beneath the top. These deposits are, therefore, classified with the *daviesi* Subzone.

In Section 3 at Water Lane, the *lautus-nitidus* Subzone was located in a shell seam at a level thirteen inches beneath Division D in which poorly preserved *Euhoplites lautus* (Parkinson MS) J. Sowerby and *E. truncatus* Spath were seen. The shell seam containing *Anahoplites daviesi* was located at a depth of about two inches below Division D. In Section 4, *Anahoplites* *daviesi* and the variety *ornata* were obtained at a level four inches beneath Division D.

Division D contains an ammonite fauna preserved in three modes, well seen in Section 2: (a) as abraded fragmentary casts in dark brown or black phosphate; (b) in blackish phosphate with portions of the shell; and (c) partly phosphatised with the shell. The size of the nodules, and the fragmentary fossils preserved in mode (a), composing the bulk of D is quite small. Badly abraded ammonites indicate that the *daviesi* Subzone may be partly represented. The ammonites preserved in mode (c) consist of both *daviesi* and *cristatum* Subzone forms, but all the *daviesi* Subzone ammonites found preserved in this manner were obtained from the base of the Division. The bulk of the ammonites preserved in modes (a) and (b), however, belong to the *cristatum* Subzone. Fossils include:

> *Hamites maximus* J. Sowerby (a.b.), and the variety *rectus* Brown (a), *H. gibbosus* J. Sowerby (a), *H.* cf. *incurvatus* Brown, *Beudanticeras* cf. *beudanti* (Brongniart), *B. sphaerotum* ? (Seeley), *B. subparandieri* Spath, *Euhoplites* aff. *truncatus* Spath (a), *E. opalinus* Spath (c), *E.* aff. *proboscideus* (J. Sowerby) b.c., *E.* aff. *armatus* Spath (a.b), *E.* cf. *trapezoidalis* Spath, and the var. *formosa* Spath, *E. ochetonotus* (Seeley), *E.* aff. *sublautus* Spath (c), and the var. *monocantha* Spath (c), *Anahoplites splendens* (J. Sowerby), *A. planus* (Mantell) a, b, and the variety *compressa* Spath (b) and forma *fittoni* (d'Archiac) b, *A.* cf. *daviesi* Spath, *Dimorphoplites* aff. *glaber* Spath, *D. chloris* Spath (a), *D.* aff. *biplicatus* (Mantell), *D. tethydis* (Bayle) *D.* spp., *D.* ? *silenus* Spath (a), *Epihoplites metamorphicus* Spath (a), *E. compressus* (Parona and Bonarelli), *E. trifidus* (Spath) a, *E.* spp., *Dipoloceras cristatum* (Deluc MS) Brongniart, and varieties *subcristata* (Deluc MS) Brongniart and *alata* Spath, *D.* sp., *Eutrephoceras* sp. *Pseudocenoceras* sp., *Neohibolites minimus* (Miller), *Inoceramus concentricus* Parkinson (a), *I. anglicus* Woods, *I. sulcatus* Parkinson (a, b) and the variety *subsulcata* Wiltshire (a), *Nucula* spp. (c), *Notopocorystes stokesii* (Mantell), *Isocrinus* ossicles.

Crushed fossils, unquestionably of *cristatum* Subzone age, also occur in this bed and include species of *Anahoplites*, *Epihoplites* and *Euhoplites*.

The overlying clays to a height of about one foot four inches, seen in Section 2, contain crushed ammonites comparable to those which occur in the upper nodule bed of Bed VIII and the lower part of Bed IX at Folkestone. This was immediately followed by a thin shell seam with partly phosphatised ammonites containing, amongst others, *Beudanticeras beudanti* (Brongniart), *Anahoplites* aff. *picteti* Spath, and *Euhoplites sublautus* Spath. This in turn is followed by clay containing a typical *orbignyi* Subzone fauna with species of *Hysteroceras*, *Mortoniceras* and *Epihoplites* occurring in shell seams.

4. CORRELATION

In order not to infringe the forthcoming account of the section in the Rugby Portland Cement Company pit near Trottiscliffe, Kent, the correlation of the Junction beds in the By-Pass is made with the Folkestone section only, and that of the Lower Gault with the Folkestone and Sevenoaks Brick Works sections (Figs. 1 and 2).

(*i*) *Gault–Lower Greensand Junction*. The ammonites obtained from Bed 5(i) and 6 at Chrismill Bridge are comparable to crushed or partly phosphatised ammonites which occur in Bed 1a at Folkestone. This indigenous fauna is associated with the semi-derived fossils which abound in this bed (Casey, 1950, 1959). At Chrismill, beds 8–10 probably correspond to the Sulphur Band, and beds 11–15 to the Greensand Seam, at Folksetone.

(*ii*) *Lower Gault*. The Lower Gault in Section 4 of the Maidstone By-Pass is twenty-six feet thick in comparison with a maximum of about thirty-three feet measured at Folkestone, which is thicker than recorded by Price (1879), and thirty-seven feet exposed at Greatness. The six well-marked lithological divisions in the Lower Gault of the Sevenoaks Brick Works pit, Greatness Lane, Otford (incorrectly recorded as Sevenoaks, Milbourne, 1956; Owen, 1958), cannot be wholly recognised in the Maidstone By-Pass.

Division A in the By-Pass contains an ammonite fauna which shows it to be earlier than the upper *dentatus-spathi* nodule bed in the northern Weald (Owen, 1958), and may be correlated with the *dentatus*-nodule bed in Bed I at Folkestone, and at least the upper foot of Division 1 at Greatness below the upper *dentatus-spathi* nodule bed. The predominance in Division A of *Hoplites* of the *persulcatus* group, the comparative rarity of the typical *H. dentatus*, and the occurrence of a variety of *Hoplites latesulcatus* Spath transitional from *H. persulcatus*, indicate, however, that it does not cover as great a time interval as does the Folkestone nodule bed. At Folkestone, the variety of *H. latesulcatus* occurs as fragments, according to the writers collecting, and many of the ammonites recorded above as *Hoplites* spp. are morphologically intermediate between those found commonly in the *dentatus* nodule bed at Folkestone, and those found in the upper *dentatus-spathi* nodule bed in NW. Kent and Surrey. It is possible that the top of the Gault–Lower Greensand Junction in the By-Pass might be of earliest *dentatus-spathi* age. There is, therefore, evidence to suggest that the principal bed of phosphatic nodules in the *dentatus-spathi* Subzone in the northern Weald is diachronous, becoming younger in age as it is traced westwards from Folkestone.

The evidence for this view is further supported by the less condensed sequence in the *dentatus-spathi* Subzone in the Nyewood Brick and Tile Works Limited pit, at Nyewood, Rogate, Sussex. Towards the top of the pit, under clays containing the upper *dentatus-spathi* nodule bed fauna, there is a ferruginous band about eight inches thick with partly phosphatised species of *Hoplites*. *Hoplites* of the *persulcatus* group are common in this band, and the transitional variety of *H. latesulcatus* mentioned above also occurs. Below this bed there are clays which, with the ferruginous band, may be correlated with the *dentatus* nodule bed in Bed I at Folkestone. Division A in the Maidstone By-Pass at least includes the lateral equivalent of the ferruginous band at Nyewood. The lower six feet five inches of Division B is correlated with the upper part of Bed I at Folkestone up to the base of the *intermedius* Subzone, and with the upper *dentatus-spathi* nodule bed (Division 2) and the lower two feet nine inches of Division 3 at Greatness.

The *intermedius* Subzone includes the remainder of Division B and the lower part of C(i). Together, they are comparable in thickness to the upper part of Bed I and the bulk of Bed II classified with this Subzone. At Greatness the *intermedius* Subzone is thicker and includes the remainder of Division 3.

In the By-Pass, the *niobe* Subzone includes the remainder of C(i) and is correlated with Bed III at Folkestone and the lower two feet two inches of Division 4 at Greatness.

Division C(ii), classified with the *subdelaruei* Subzone, may be correlated with Bed IV (i) and (ii) at Folkestone (Owen, 1958). At Greatness, the *subdelaruei* Subzone is represented within the remaining five feet ten inches of Division 4 and the lower two feet eleven inches of Division 5. The deposits of *subdelaruei* Subzone age, therefore, expand considerably westwards from Maidstone.

The lower two feet five inches of C(iii) is correlated with Bed IV(iii) and the basal few inches of Bed V at Folkestone, and with the three feet three inches of Division 5 (erroneously given as two feet five inches; Owen 1958, 158) of equivalent age at Greatness. *Euhoplites meandrinus* Spath is a characteristic ammonite of deposits of this age in SE. England and it is suggested here that this Subzone be known as the *meandrinus* Subzone. The Subzone is developed elsewhere in NW. Kent and beneath the *lautus-nitidus* Subzone in the British Portland Cement Company pit at Horton Hall, near Small Dole, Sussex.

The *lautus-nitidus* Subzone is entirely represented by clays in the By-Pass from a level one foot six inches below the top of C(iii) to a level four inches below the top. These deposits may be correlated with the remainder of Bed V, Bed VI, and the lower part of Bed VII at Folkestone. At Greatness, the Subzone is represented by the five inches of clay at the top of Division 5 and within the semi-derived fauna of Division 6, the *lautus* Zone nodule bed.

The upper four inches of Division C(iii) may be correlated with most of the remaining portion of Bed VII at Folkestone. However, the uppermost part of Bed VII is represented within Division D, the *cristatum* nodule bed in the By-Pass. At Greatness, the *daviesi* Subzone is represented entirely in the semi-derived fauna of the *lautus* Zone nodule bed, Division 6.

Division D is also correlated with Bed VIII at Folkestone, but in

Section 2 the clays immediately above Division D might also be correlated with that bed. The upper nodule bed of Bed VIII is largely composed of partly phosphatised ammonites and does not mark as great a time interval as does the lower nodule bed. Division D is represented within Division 6 at Greatness.

At Folkestone, therefore, the *lautus-nitidus* and *daviesi* Subzones are represented entirely by clays, and the principal erosion levels marked by phosphatic nodules affect deposits of the *cristatum* Subzone only. In the Maidstone By-Pass, the *daviesi* Subzone is thinly represented by clays underlying the *cristatum* Subzone nodule bed, and in the semi-derived fauna of the nodule bed. At Greatness, the *daviesi* Subzone is entirely represented by semi-derived fossils within Division 6, the *lautus* Zone nodule bed and the *lautus-nitidus* Subzone is in turn thinly represented in the clays beneath. Still farther west, in the Reigate area, the *lautus* Zone nodule bed is apparently absent (Gossling, 1929) and deposits of restricted *lautus* Zone age have not yet been found.

The transgressive nature of the nodule bed at the top of the Lower Gault, as it is traced westwards from Folkestone around the northern Weald, indicates that during *cristatum* Subzone times slight tilting up occurred in a westerly direction. The surface of the Lower Gault sediments was planed off and the phosphatised fossils present in these sediments were washed out and redeposited together in the *cristatum* nodule bed and its westerly extension, the *lautus* Zone nodule bed. The abraded nature of the phosphatic casts and the tendency for the nodules to collect in pockets indicates that strong swirling current action was effective during the course of this erosion.

The occurrence of ammonites of *meandrinus* Subzone age, such as *Euhoplites aspasia* var. *cantiana* Spath, as abraded casts in Division 6 at Greatness suggests that fossils were washed out of sediments of that age and were carried eastwards before deposition. The indigenous fauna of the nodule bed in all sections examined by the writer in Kent is of *cristatum* Subzone age, a fact which should not be overlooked by workers studying the foraminifera of the Lower Gault. At the base of the nodule bed, partly phosphatised fossils of the same age as the clays beneath may be present, and due to the irregular nature of the nodule bed these might easily appear to belong to its indigenous fauna.

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The author would like to thank Mr. H. A. Toombs for criticism of the original manuscript, and Dr. L. R. Cox, Mr. L. Bairstow and Dr. H. W. Ball, of the Department of Palaeontology, British Museum (Natural History), for identification of, or comments on, some of the fossils listed here; also to thank Mr. E. W. H. Vallis of Kent County Council and the Chief Engineers, Mr. Thomason and Mr. J. H. Matthews, of Messrs. Richard Costain Limited for facilities kindly afforded by them and the members of their staff.

REFERENCES

Brown, H. J. W. 1930. Notes on the Geology of the Vale of Holmesdale, between Maidstone and Lenham. *Proc. Croydon Nat. Hist. Sci. Soc.*, **10,** 110–15.

Casey, R. 1950. The Junction of the Gault and Lower Greensand in East Sussex and at Folkestone, Kent. *Proc. Geol. Ass., Lond.*, **61,** 268–97.

———. 1959. Field Meeting at Wrotham and the Maidstone By-Pass. *Proc. Geol. Ass., Lond.*, **70,** 206–9.

Dines, H. G., S. C. A. Holmes & J. Robbie. 1954. Geology of the Country around Chatham. *Mem. geol. Surv. U.K.*, 272 (N.S.). Palaeontology by R. V. Melville.

Geological Survey of Great Britain. 1958. *Summary of Progress for 1957.*

Gossling, F. 1929. The Geology of the Country around Reigate. *Proc. Geol. Ass., Lond.*, **40,** 197–259.

Jukes-Browne, A. J. 1900. The Cretaceous Rocks of Britain. 1. Gault and Upper Greensand of England. *Mem. geol. Surv. U.K.*

Milbourne, R. A. 1956. The Gault at Greatness Lane, Sevenoaks, Kent. *Proc. Geol. Ass., Lond.*, **66,** 235–42.

Owen, H. G. 1958. Lower Gault Sections in the Northern Weald and the Zoning of the Lower Gault. *Proc. Geol. Ass., Lond.*, **69,** 148–65.

Price, F. G. H. 1879 and 1880. *The Gault*, London.

Spath, L. F. 1925. A Monograph of the Ammonoidea of the Gault. Part III. *Palaeontogr. Soc.* (*Monogr.*).

———. 1926. On the Zones of the Cenomanian and the Uppermost Albian. *Proc. Geol. Ass., Lond.*, **37,** 420–32.

———. 1943. A Monograph of the Ammonoidea of the Gault. *Palaeontogr. Soc.* (*Monogr.*).

The Limit of the 'Last' Glaciation in North Norfolk

by ALLAN STRAW

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ABSTRACT: The maximum southerly extent of ice in North Norfolk during the Last Glaciation coincides closely with the 100-foot contour between Heacham and Holkham, and instances of marginal drainage occur at Ringstead, Holkham and Warham. The glacial features of the area compare closely with those of East Lincolnshire, and investigation of the 'fresh' glacial landforms noted by Solomon (1932) and West (1957) between Morston and Weybourne, suggests that they have been produced rather by the erosion of Older Drift than by deposition of Newer Drift.

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1. INTRODUCTION

AS A SEQUEL to work on the glacial morphology of East Lincolnshire, and in the light of conclusions reached regarding the glacial history of that area, an investigation was made in 1958 into the glacial features of the North Norfolk coast.

In East Lincolnshire, the various drifts are referable to the Gipping and Last glaciations, and, as the 'Hessle' drifts of the Lincolnshire 'Marsh' were emplaced after a long period of weathering and erosion had affected the Chalky Boulder-Clay, marked morphological contrasts are displayed (Straw, 1958).

Various workers, in describing the drifts of the North Norfolk coast, have referred to a low-lying brown boulder-clay, which Woodward (1884) and Solomon (1932) firmly considered to be the equivalent of the 'Hessle' Till of Lincolnshire and Yorkshire.

The investigation in North Norfolk was therefore directed towards establishing whether the topographic features and relationships of this so-called 'Hunstanton' boulder-clay were sufficiently similar to those of the 'Hessle' tills in Lincolnshire to merit unqualified support of the suggested correlation.

2. CHARACTER OF THE 'HUNSTANTON' BOULDER-CLAY

Descriptions of certain exposures in this boulder-clay and associated gravels have been given by Whitaker & Jukes-Browne (1899), Woodward (1884), Solomon (1932), Baden-Powell (1944), and Chatwin (1954).

The till is generally red-brown or grey-brown in colour, sandy or loamy in texture, with much less chalk and flint than the Chalky Boulder-Clay, but containing numerous and varied small erratics, including igneous rocks of Cheviot type. The erratic content is, however, variable, and the till frequently passes into brown sandy loam with few stones. The till is thickest on the low ground bordering the alluvium, but on steeper slopes its former presence is still amply shown by the occurrence of the characteristic erratics in soils that are very sandy and red-brown in colour. The distribution of such soils ('drift-soils') is considered to indicate closely the maximum extent of the ice. Along the former margin of the ice-sheet, certain glacio-fluvial features occur. Recognition of such features contributes to the definition of this margin.

Exposures of brown stony clay in other parts of North Norfolk, particularly around Happisburgh, have been described by S. V. Wood (1872) and D. F. W. Baden-Powell (1944). It is considered here, however, that this stony clay is 'head', derived largely from the underlying and much older glacial deposits, and probably contemporaneous with the 'Hunstanton' boulder-clay. Erratics in the stony clay, as noted by Baden-Powell, are mainly hard sandstones and small quartzites with occasional basalts, and the author has frequently observed in North Norfolk and East Lincolnshire that these resistant types of rock are now the only erratics, excluding flint, included in remanié drifts or 'head' derived from glacial deposits of pre-'Hessle' age.

3. THE LIMIT OF THE 'HUNSTANTON' BOULDER-CLAY

(a) Heacham to Brancaster

In the west, the boulder-clay first appears as a low ridge rising NNE. from the Fen alluvium at ten to fifteen feet O.D. to fifty feet O.D. in Heacham. Here the drift becomes embanked against the Sandringham Sands to form a low platform above the alluvium as far north as Hunstanton. On the steeper slopes above this platform, 'drift-soils' and erratics occur up to ninety feet O.D., but are absent from the ridge of Chalk that rises just over 100 feet O.D. east of New Hunstanton. The platform disappears as the Cretaceous rocks reach the coast, but brown boulder-clay recurs at fifty feet O.D. just north of Hunstanton station.

'Drift-soils' overspread most of Hunstanton Park, which occupies a wide shallow valley below the 100-foot contour, but they do not extend south of a gorge-like valley lying south-west of Ringstead (Fig. 1). This valley appears to have cut through the side of a broader valley which, still evident east of Ringstead, was formerly continuous with the valley through Hunstanton Park. East of Ringstead, the valley is floored by a level expanse of gravels, derived in large part from the surrounding slopes. These gravels indicate the former presence of a small pro-glacial lake that would have been created when ice advanced into the Hunstanton Park section of the valley. This lake overflowed west along the southern margin of the ice, the escaping waters presumably excavating the gorge south-west of Ringstead, and so isolating the Chalk ridge at New Hunstanton. This water was apparently augmented by a glacial stream which deposited the fine esker in Hunstanton Park, and was later diverted south along the ice-edge through Heacham.

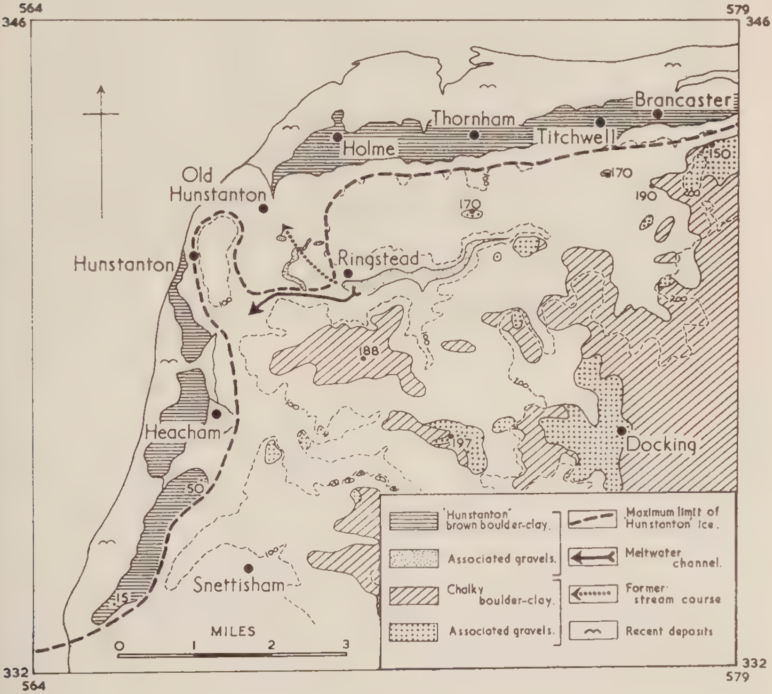

Fig. 1

As shown in Fig. 1, an ice-lobe obviously pressed south towards Ringstead, but the main mass of ice was obstructed by the steep Chalk slopes occurring behind Holme and Thornham. On these slopes, 'drift-soils' with the characteristic erratics are present up to 100 feet O.D. A patch of flinty gravel related to the Chalky Boulder-Clay surmounts Beacon Hill, south of Thornham, at 170 feet O.D.

(b) Brancaster to Wells

Near Brancaster, the erratics may be found up to 120 feet O.D., but their limit then lowers slightly towards the Burnhams (Fig. 2). Here, where the steep Chalk slopes are broken by a group of northward-draining valleys, the ice appears once more to have extended farther south. The small youthful valley south-west of Burnham Deepdale contains no 'Hunstanton' drifts, but gravels from beneath the Chalky Boulder-Clay outcrop above 120 feet O.D. South of Burnham Deepdale, a narrow strip of gravel lies at 75–100 feet O.D., and again marks the former ice margin. This gravel apparently rests on a Chalky clay (Whitaker & Jukes-Browne, 1899, 79), but as the clay lies some fifty feet below the almost horizontal base of the sub-Chalky Boulder-Clay gravels, it is probably 'head' originating from the drift-free Chalk slopes above. Other gravels lie on the flanks of the Burnham Norton valley at eighty feet O.D. in terrace-like manner, but the larger valley south-west of Burnham Market is free of the brown drifts. Between these valleys, the broad interfluves are capped by Chalky Boulder-Clay, which tongues northward from the extensive 200-foot plateau between Docking and North Creake. From south of Brancaster, the base of the Chalky Boulder-Clay descends gently east from 180 feet O.D., to 140 feet O.D. south-west of Burnham Market, 100 feet O.D. south of this village,

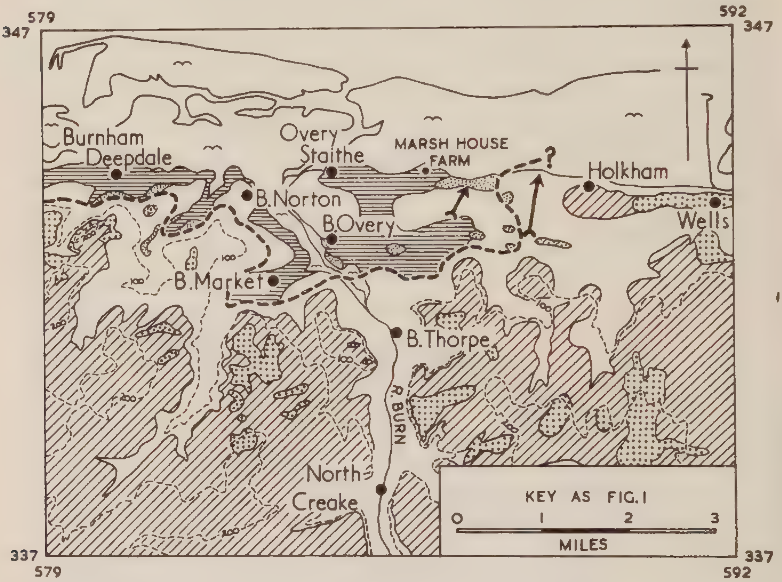

Fig. 2

and only fifty feet O.D. to the south-east. It then rises to 100 feet O.D. east of Burnham Thorpe. The Chalky Boulder-Clay thus occupies an old wide valley, the line of which is generally followed by the present River Burn.

South of Burnham Thorpe, the Burn is incised into the plateau of Chalky Boulder-Clay and gravel, the latter appearing in places to outcrop from beneath the boulder-clay, such as ENE. of North Creake. The gravel consists of coarse subangular flint pebbles with much rolled chalk, but only rare foreign erratics. As a result of considerable dissection, these gravels form small but bold spurs or terrace-like features, but similar features are also formed elsewhere by gravels overlying the Chalky Boulder-Clay, for instance around Quarles Farm (53/883387) two miles ENE. of North Creake. These latter gravels lie generally on or above 200 feet O.D. Such features, occurring on the brows of the valley-sides, are obviously due to erosion, as the Burn has cut through the Chalky drifts and now flows on Chalk through South Creake and North Creake to Burnham Thorpe. South-east of Burnham Overy, however, several irregularly placed low mounds, rising to fifty feet O.D., lie in the floor of the valley. These consist of silty brown sand, a particularly large one having limited flood-plain development near Burnham Overy mill. Just north of Burnham Market, sandy soils with many angular flint chips and several small igneous erratics occur at fifty feet O.D. Brown boulder-clay has been exposed one and a quarter miles to the east of Burnham Overy in the Peterstone brickworks.

'Hunstanton' drifts are therefore present in the floor of the Burn valley between Burnham Market and Peterstone Farm (53/861430), the low mounds being terminal deposits of an ice-lobe that pressed into the lower part of the Burn valley (Fig. 2). This lobe appears to have extended east into Holkham Park as far as Howe Hill (53/878431). The lake in the Park occupies a curious valley cut across a low ridge of Chalk that extends west from Wells to Overy Staithe. The valley lies immediately east of Howe Hill and may have functioned as a spillway at some time for water from the Burn valley that found its way eastward along the south side of the ice-lobe. Another short transverse valley is followed by the railway at the north-west corner of the Park, and may also have been excavated largely by meltwaters.

On the north side of the low Chalk ridge, which west of the lake appears to have been just covered by ice, the 'Hunstanton' drift forms a low terrace from Overy Staithe to Marsh House Farm. East of this farm, the 'Hunstanton' drift does not reappear on the coast for several miles.

From Burnham Thorpe, the base of the Chalky Boulder-Clay resumes its eastward declination, occurring on spurs in Holkham Park at ninety feet O.D., and in the railway cutting south-east of Wells at fifty feet O.D. Chalky Boulder-Clay and associated gravels also cap that portion of the low Chalk ridge trending east from Holkham Park lake to Wells. Thus Chalky Boulder-Clay comes near the coast at Wells, capping the steeper Chalk slopes that rise immediately from the salt marshes.

(c) Wells to Morston

East of Wells, the Chalky Boulder-Clay is cut by the River Stiffkey, the lower section of which exhibits a curious course (Fig. 3).

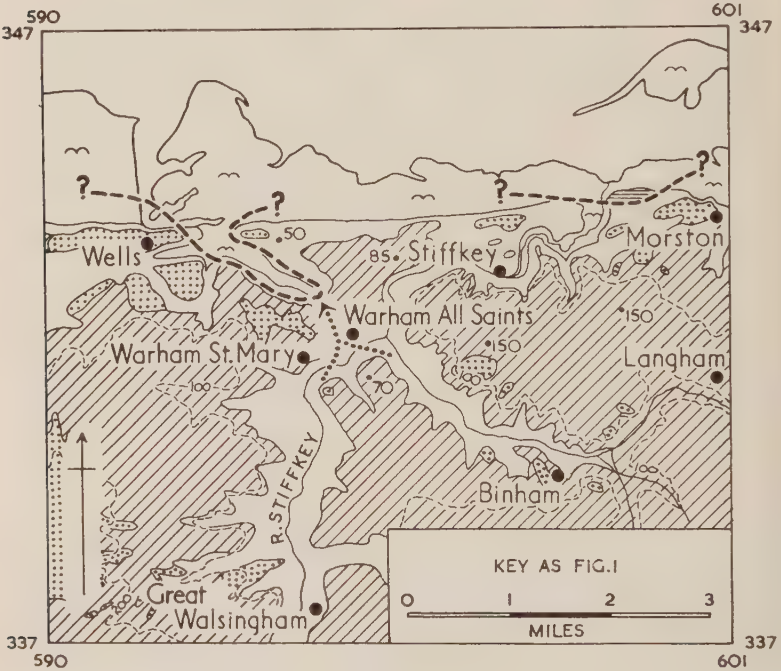

Fig. 3

Through Great Walsingham to Warham, the river flows north in a broad valley cut into the Chalk below the Chalky Boulder-Clay. At Warham All Saints it receives the north-westerly-directed Binham Beck, and then turns north-east in a narrow sinuous valley to reach the coast north-west of Morston. The line of Binham Beck is continued to Wells by a broad but short valley largely floored by marine alluvium. The head of this valley seems to have been truncated by the Stiffkey valley, and a col some twenty to thirty feet above the floor of the latter now exists between Warham St. Mary and Warham All Saints. It is not unreasonable to suggest that the River Stiffkey together with Binham Beck formerly reached the coast just east of Wells by way of this short valley. If so, then clearly the lower Stiffkey has suffered diversion from Warham to Morston.

As the Chalky Boulder-Clay surface declines west across the lower Stiffkey valley from 140 to 60 feet O.D., it seems unlikely that the river was captured by the headward erosion of a stream flowing through Stiffkey village. Nor can the diversion of the river have been accomplished early in the development of the system (i.e. immediately after Chalky Boulder-Clay times), for the Stiffkey valley above Warham is wider and gentler than the youthful lower section, the ravine-like tributary valleys near Stiffkey village contrast sharply with the tributary valleys south of Warham, and the col at Warham All Saints is too well developed. It would appear therefore that diversion took place during a late stage in the incision of the Stiffkey–Binham Beck valley, and was due to some obstruction in the lower section of the valley between Warham and Wells. Such obstruction can only have been ice, and was most likely the ice which laid down the 'Hunstanton' boulder-clay farther west. It is significant that the lower Stiffkey crosses the Chalky Boulder-Clay plateau just on the 100-foot contour (Warborough Hill (53/961434), 105 feet O.D.), a height which appears critical in the distribution of the 'Hunstanton' drift.

Confirmatory evidence for an ice-lobe in the Warham–Wells valley is scanty, but the hummocky nature of the floor of the col around North Hall Farm, and a record by Woodward (1884, 37) of a pit showing six feet of brown sand with gravelly seams (at sixty feet O.D.) east of Warham St. Mary's Church, lend some support.

This ice-lobe does not appear to have overspread the area of Chalky Boulder-Clay north of Warham All Saints up to the edge of the Stiffkey valley. The surface slopes gently WSW. from Warborough Hill, and presumably higher ground to the north of Warborough Hill formerly existed against which the ice lay. This higher ground, together with all traces of the ice-sheet, except west of Morston, may have been removed by cliff recession after withdrawal of the ice-sheet, but prior to the accumulation of the salt marshes. Such cliff erosion could also have removed similar traces between Wells and Marsh House Farm, west of Holkham (Fig. 2).

The final appearance of 'Hunstanton' drift is near the mouth of the River Stiffkey, where Solomon (1932, 257) records three feet of sandy brown boulder-clay resting on raised beach deposits.

(d) Summary

The main points arising from the foregoing delimitation of the maximum limit of the 'Hunstanton' ice-sheet in North Norfolk may be briefly tabulated.

(i) Rarely do the 'Hunstanton' drifts occur above 100 feet O.D.
(ii) Ice-margin erosion features at Ringstead, Holkham and Warham occur at or below the 100-foot contour.
(iii) Nowhere does the 'Hunstanton' boulder-clay come in contact with the Chalky Boulder-Clay, for it is always separated from it by drift-free slopes of Chalk.
(iv) The attitude of the 'Hunstanton' boulder-clay is in marked contrast to that of the Chalky Boulder-Clay, as the former occupies the floors of valleys that have been excavated through the latter.
(v) East of Hunstanton the brown boulder-clay is largely banked against a generally steep and remarkably regular slope of Chalk.
(vi) Emplacement of the 'Hunstanton' drifts was closely controlled by details of present topography.
(vii) The geomorphology of the coastal area east of Morston suggests that the 'Hunstanton' ice-sheet did not reach this coast again.
(viii) The 'Hunstanton' ice-sheet nowhere reached the Cromer moraine.

4. COMPARISON WITH EAST LINCOLNSHIRE

In this wider context, the following observations may be made.

a. The close regard to the 100-foot contour as an upper limit of the ice is exactly paralleled by the 'Hessle' ice on the south side of the Lincolnshire Wolds.
b. The ridge of brown boulder-clay at Heacham has a similar form to the ridge of 'Hessle' boulder-clay at Stickney, north of Boston.
c. A long period of erosion followed emplacement of the Chalky Boulder-Clay and preceded the deposition of the 'Hunstanton' drift, during which the Chalky Boulder-Clay was strongly dissected by valleys which were not only cut through this drift but were also excavated some fifty to eighty feet into the Chalk. Such a period of erosion is of interglacial character, and this sequence of events is equally apparent in East Lincolnshire.
d. The regular Chalk slopes, against which the 'Hunstanton' boulder-clay is banked, form a sharp northern limit to the Chalky Boulder-Clay plateau, which shows no sign of declining towards it. The Chalk bluff therefore truncates the Chalky Boulder-Clay, and, pre-dating the brown boulder-clay, must have been formed in the interglacial period. The straightness of the bluff, and its continuation by obvious former cliffs east of Holkham suggest that it too is the result of marine erosion. The feature has an identical counterpart in East Lincolnshire.

Geomorphological evidence is therefore entirely in accord with the suggestion by Solomon, that the brown boulder-clays of North Norfolk are the equivalent of the 'Hessle' tills of East Lincolnshire and Yorkshire, and it is considered by the author that they were emplaced by the same ice-sheet during the Last Glaciation, although it is noted that this is contrary to the views recently expressed by Valentin (1957).

5. GEOMORPHOLOGY OF THE COASTAL REGION BETWEEN MORSTON AND WEYBOURNE

The conclusion that the Last ice-sheet did not cross the Norfolk coast east of Morston may perhaps be questioned by the presence of certain fresh-looking features between Blakeney and Weybourne. Solomon (1932, 257) regarded these features as kames and eskers, and his views have recently been amplified by West (1957) who has since (1958) suggested the possibility that the features were formed at the same time as the 'Hunstanton' boulder-clay. Although this boulder-clay was deposited during the Last Glaciation, apart from the few instances of drainage diversions, the esker in Hunstanton Park, and the low irregular mounds of drift near Burnham, no really fresh glacial topography exists. It seems strange therefore that constructional landforms such as kames and eskers, including the Blakeney ridge and Muckleburgh Hill (63/101429) as mentioned by Solomon, and several supposed kames and kame-terraces in the Glaven valley described by West, should be recognised in areas outside the limit of the 'Hunstanton' boulder-clay.

These features are composed of glacial gravels which consist predominantly of flint; only rarely can foreign erratics be found. In many instances, as at the west end of the Blakeney ridge, in Warborough Hill, and just south of Glandford, the gravels are closely associated with typical Chalky Boulder-Clay. Nowhere do the gravels contain any boulders characteristic of the 'Hunstanton' boulder-clay. Further, the gravel features lie generally above 100 feet O.D., which demonstrably marks the upper limit of the drifts and features associated with the 'Hunstanton' ice. A not unreasonable alternative exists, in that these features are not constructional, but largely erosional.

A glance at Fig. 4 shows immediately that the River Glaven has cut through the Chalky Boulder-Clay into the Chalk, and similar incision of the Burn and Stiffkey valleys is deemed to have taken place mainly during the Last Interglacial. Between Morston and Weybourne, the Chalky boulder-clay overlooks the marshes from the top of old Chalk cliffs some fifty feet in height, which continue the interglacial cliffs preserved west of Morston. The cliffs thus truncate the Chalky Boulder-Clay and sever the north-western end of the Blakeney ridge. This ridge is transected by the Glaven valley, the floor of which is some eighty to ninety feet below the base of the ridge gravels, a situation which indicates that the ridge was formed prior to the interglacial period.

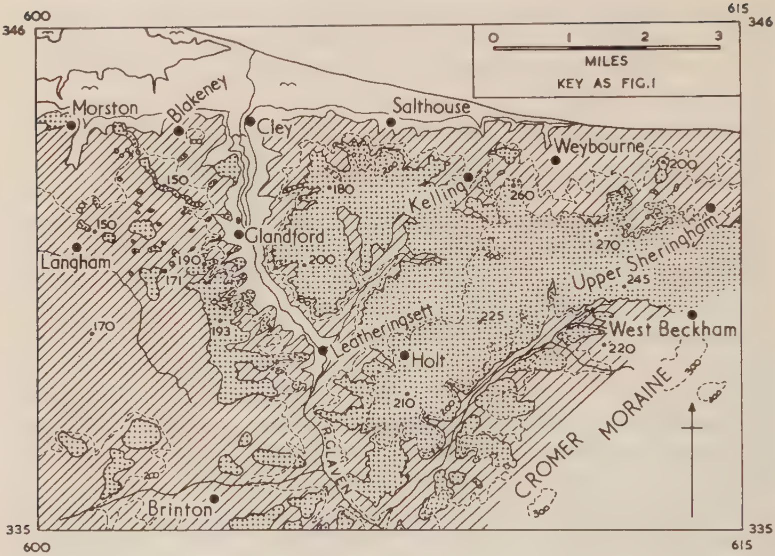

Fig. 4

East of the Glaven valley, the extensive gravel spreads of Salthouse and Kelling Heaths, the latter reaching south beyond Holt, may be truly regarded as outwash plains, but they too have suffered considerable dissection by the Glaven and its tributaries. The Kelling–Holt sandür apparently stretched as far south as the Cromer moraine, which, forming ground rising over 300 feet O.D. between West Beckham and Edgefield, acts as the present divide between the Bure and Glaven drainage. The southern margin of the gravel is now modified by the south-westerly flowing headwaters of the Glaven. On the northern margin, between Kelling and Upper Sheringham, excessive erosion of the gravels is evident. An abrupt break of slope at the base of the gravel indicates active spring-sapping, but, as West suggests (1957, 28), accelerated erosion under periglacial conditions may be held responsible for the pronounced fretting of the margin. Identical erosion has occurred on the north and west sides of Salthouse Heath, and appears no less well developed on the west side of the Glaven valley between Leatheringsett and Glandford. Removal of the gravel is resulting in the production of gently inclined surfaces of Chalky Boulder-Clay between Weybourne and Upper Sheringham, around Kelling, and between Salthouse and Cley. The surfaces still carry outliers of the gravels, such as that in Oakwood, north-west of Upper Sheringham, and Muckleburgh Hill, west of Weybourne. This latter feature was interpreted by both Solomon and West as a kame, but an erosional origin seems more likely.

The landforms between Upper Sheringham and Cley therefore indicate that marked southerly recession of the gravel margin has taken place, and, clearly, the latter cannot be regarded as an ice-contact slope.

Conversely, the form and position of the Blakeney ridge suggests that it is an ice-marginal feature. It lies almost wholly between 100 and 150 feet O.D., and has a core of very chalky silt at its north-west end. In this locality, the gravels dip northward, while on that section known as the Downs, the gravels, including thick seams of fine sand, lie horizontally. This latter occurrence, in association with the innumerable patches of gravel that lie on the Chalky Boulder-Clay to the south-west and south, suggest that a more continuous sheet of gravel formerly existed. It is not inconceivable that this accumulated in front of an ice-edge that lay along the north side of the Blakeney ridge, but the latter owes its present form largely to the excavation of two short deep valleys, one directed north-west to Morston, the other south-east to Glandford, both of which may also have originated as ice-marginal features. Similarly the gravels of Hammer Hill rest on a narrow spur to the north of a deep tributary gully of the Glaven. The Blakeney ridge may therefore have arisen through a combination of meltwater deposition and erosion, on the south side of a receding ice-lobe, during Chalky Boulder-Clay times. Two previous halts in the retreat of this lobe may have allowed the initiation of (a) the Upper Glaven and Brinton Beck, and (b) the valley north-east of Leatheringsett, separating Salthouse and Kelling Heaths, and Langham Beck (Fig. 4).

South of Glandford, other east–west ridges of gravel occupy interfluve positions between springsapped gullies. A complication arises here, as gravels also outcrop on the valley side from beneath the Chalky Boulder-Clay, so that sapping occurs on two horizons, and this has led to the production of many kame-like mounds of gravel, some resting on Chalk, some on boulder-clay.

The fresh-looking landforms to be found in and around the Glaven valley, and to the east, thus appear to be the result of long-continued erosion, rather than of recent glacial deposition. Such erosion would have commenced immediately after the withdrawal of the Chalky Boulder-Clay ice, and, intensified during the Last Glaciation, has continued unchecked since then.

6. CONCLUSION

The topographic features of the North Norfolk coast are considered to have originated entirely since the deposition of the Chalky Boulder-Clay.

The Glaven, Stiffkey and Burn have been superimposed from this drift surface and their valleys excavated mostly during the Last Interglacial. In this period marine erosion produced mature cliffs from Hunstanton eastwards, and perhaps southwards. The main landforms were therefore in existence at the beginning of the Last Glaciation, and the effect of the latter was limited to the addition of minor depositional, glacio-fluvial and periglacial features, while saltmarsh accumulation to the west of, and cliff erosion to the east of, Weybourne have proceeded during post-glacial times.

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REFERENCES

Baden-Powell, D. F. W. & J. Reid Moir. 1944. On the Occurrence of Hessle Boulder-clay at Happisburgh, Norfolk, Containing a Flint Core. *Geol. Mag.*, **81**, 207.

Chatwin, C. P. 1954. East Anglia and Adjoining Areas. *Brit. reg. Geol.* Third Edition.

Solomon, J. D. 1932. The Glacial Succession on the North Norfolk Coast. *Proc. Geol. Ass., Lond.*, **43**, 241.

Straw, A. 1958. The Glacial Sequence in Lincolnshire. *East Midland Geographer*, No. 9 (June), 29.

Valentin, H. 1957. Glazialmorphologische untersuchungen in Ostengland. *Abh. Geogr. Inst. Freie Univ. Berlin*, **4**.

West, R. G. 1957. Notes on a Preliminary Map of some Features of the Drift Topography around Holt and Cromer, Norfolk. *Trans. Norfolk Norw. Nat. Soc.*, **18**, 24.

————. 1958. The Pleistocene Epoch in East Anglia. *Journal of Glaciology*, **3** (23), 211.

Whitaker, W. & A. J. Jukes-Browne. 1899. Geology of the Borders of the Wash. *Mem. geol. Surv. U.K.*

Wood, S. V. 1872. Supplement to the 'Crag Mollusca'. *Palaeontogr. Soc.* [*Monogr.*], Introduction, 29.

Woodward, H. B. 1884. Geology of the Country around Fakenham, Wells and Holt. *Mem. geol. Surv. U.K.*

On the Occurrence of Celestine in the Caps and Broken Beds at Durlston Head, Dorset

by IAN M. WEST

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ABSTRACT: An occurrence of celestine in the Lower Purbeck Beds at Durlston Head is described and is shown to be of syngenetic origin. Deposition probably took place near the margin of a basin of evaporite deposits into which strontium solutions were introduced. At a later date the celestine has been involved both in the brecciation that formed the Broken Beds and in complex local faulting.

1. INTRODUCTION

THE PURBECK BEDS of eastern Dorset long ago attracted geological interest. Early studies by T. Webster (1816 and 1826) were followed by the work of numerous investigators, especially W. H. Fitton (1836), O. Fisher (1856), E. Forbes (1850), and H. W. Bristow (1857). Later accounts relating to this area and summarising previous work were made by R. Damon (1860), A. Strahan (1898), H. B. Woodward (1895) and more recently by W. J. Arkell (1947).

The greatest interest has always been concentrated on the remarkable and varied fossil content ranging from the ostracods, on which the zonal subdivisions are based, to the famous mammalian remains in the Middle Purbeck Beds.

Other features have not been neglected, and much attention has been paid to the remarkable limestone breccia that constitutes the Broken Beds. Some authors have considered that the brecciation occurred when supporting material was removed from beneath, and their 'collapse hypotheses' include:

(1) removal of supporting clay (Webster, 1816);
(2) deposition of the beds over decomposing vegetation (Fisher, 1856);
(3) formation of a gash breccia (O. T. Jones, footnote *in* Arkell, 1947).

A very different view was that of Sedgwick & Murchison (1840) who regarded the Broken Beds as resulting from tectonic forces acting on relatively incompetent beds overlying the massive Portland Stone. H. B. Woodward also supported a tectonic hypothesis, and Arkell (1938a) produced evidence to show that southward adjustment movements in the middle limb of the Purbeck Fold were mainly responsible for the brecciation.

To the one major difficulty attendant on a tectonic hypothesis, the restriction of the brecciation to a definite stratigraphical horizon, Hollingworth (1938) produced an interesting explanation. He suggested that anhydrite or gypsum may once have been present in the Broken Beds (a view supported by the occurrence of gypsum at a similar horizon in Sussex) and that hydration of the anhydrite to gypsum and the subsequent solution of the gypsum may have initiated a preliminary plane of weakness on which tectonic forces acted. Arkell (1938b) at first accepted this as the probable explanation, although in 1940 he considered the possibility of small scale subaqueous slumping as providing the plane of weakness.

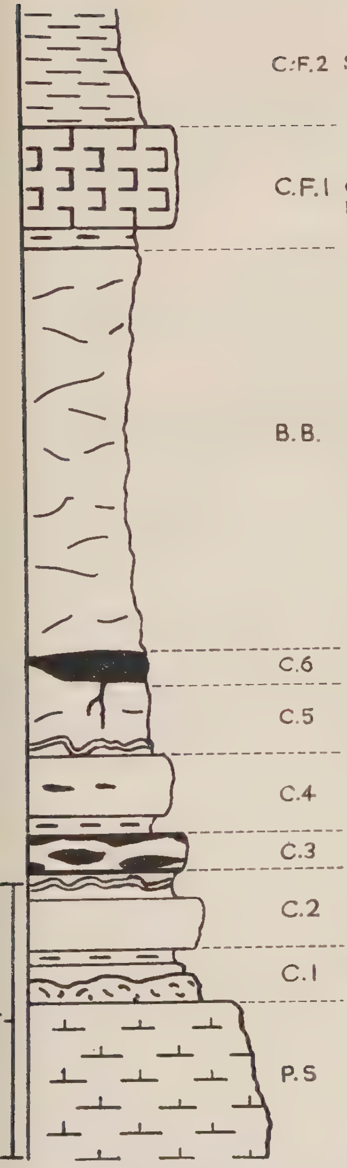
In the Broken Beds of Dorset gypsum has never been detected. Recently, however, another sulphate mineral, celestine, has been found in rock-forming quantity in the Caps and Broken Beds at Durlston Head near Swanage (Fig. 1).

2. OCCURRENCE AND FIELD RELATIONS

The mineral occurs at the foot of the cliff ENE. of Durlston Castle, on the northern downthrow side of the major fault which forms the southern end of the Durlston Bay cliff section (40/035772). (Geological Survey One Inch Map, Sheet 343, and Horizontal Section No. 56.)

In the centre of Durlston Bay, the upper part of the Broken Beds is seen on the upthrow side of a major fault, but here no celestine has been detected. Celestine also appears to be absent in the numerous cliff-top exposures of the Lower Purbeck Beds on the southern side of Durlston Head, and above the precipitous Portland Stone cliffs stretching westward to St. Aldhelm's Head.

The thicknesses of most of the numerous subdivisions of the Purbeck Beds in Durlston Bay were determined long ago (Bristow, 1857). Exceptions are the strata below the Broken Beds: these are exposed only at one point where, because of the faulting and the lithological similarity of the limestones, the succession is not easily ascertained. Referring to this exposure, Fisher wrote 'there is so much disturbance that it is impossible



Shales of the Cypris Freestone Series.

Conspicuous impure laminated limestone. Basal bed of the Cypris Freestones.

Broken Beds. Disturbed beds of limestone passing laterally into a breccia.

Upper celestine bed. Passes northward into brecciated blocks to form part of the Broken Beds.

Shaly limestone with drag folds to the north.

Laminated crystalline limestone with chert and a little celestine, becoming crushed to the north. Upper bed of the 'Soft Cap'.

Lower celestine bed. Shaly crystalline limestone with abundant celestine and with chert. Northward drag folds at the base. Lower bed of the 'Soft Cap'.

Laminated crystalline limestone } the 'Hard Cap'
Tufaceous limestone }

Portland Stone. Shrimp Bed at the top.

Fig. 1. The Succession of the Caps and Broken Beds at Durlston Head

to carry the section through satisfactorily'. H. B. Woodward mentioned the difficulties, but published a greatly oversimplified cliff section (fig. 126, p. 247).

Bristow allotted eleven feet to the Hard Cap, the lowest division of the Purbeck Beds. Correlating the beds on either side of the fault F.3 (Fig. 2), however, the author can recognise little more than four feet.

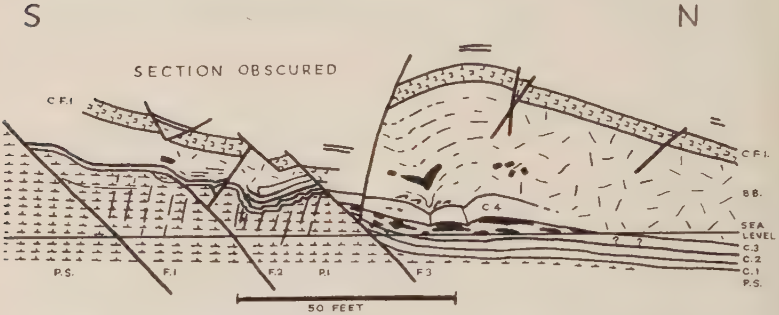


Fig. 2. Cliff section of the basal Purbeck Beds at Durlston Head. Key as in Fig. 1. Celestine is shown in black

The overlying Soft Cap, here consisting of two beds of crystalline limestone, approaches Bristow's measurement of seven and a half feet in maximum thickness. The lower bed is shaly, whilst the upper shows lateral transition into the Broken Beds. This upper bed passes northward from a crystalline limestone with small chert nodules into a crushed limestone with broken chert, and finally into a limestone breccia with conchoidally fractured chert fragments.

These Broken Beds, or 'Broken Bands' as they were originally called, are represented by up to twenty feet or more of brecciated limestone, and have been described by Bristow as 'thin slaty beds of bituminous sandy limestone much broken and squeezed together with a few broken fragments of chert'. At Durlston Head, the Broken Beds are well exposed north of fault F.3 (Fig. 2) and pass rapidly northwards from beds of disturbed, but not truly brecciated, limestone into the typical breccia. This becomes partially decalcified in a few yards, where it consists of a firm but unstratified accumulation of calcareous sand, clay and chert fragments. In this condition the partially decalcified breccia is intermittently exposed for more than a hundred yards to the north, before dipping below the level of the beach.

Overlying the Broken Beds is a bed of laminated marly limestone, four feet thick, with some shale at its base. This is the lowest bed of the Cypris Freestones and, although sometimes disturbed, it rarely loses its identity through brecciation.

The field relations of the celestine are much complicated by a series of minor faults and shears mainly trending parallel to the major east–west normal fault (F.1 in Fig. 2) downthrowing approximately twenty feet to the north. (The eighty foot throw marked on the Geological Survey Map, Sheet 343, indicates the combined effect of all these faults.)

On either side of fault F.3 (Fig. 2) the Broken Beds show a remarkable contrast in thickness. To the south the breccia is thin; but to the north, where an unusual lack of brecciation is to be seen, the strata are markedly thickened.

In this thicker northern part of the section the Broken Beds enclose a dislocated bed or lenticle of celestine–calcite rock, nine inches thick, and lying five feet above the Soft Cap. This is referred to hereafter as the upper celestine bed. It is not traceable to the south, but in the fully brecciated strata farther north it occurs as randomly orientated angular blocks, not far displaced from the original level.

The celestine blocks can only be followed for a few yards, then are lost for almost a hundred yards north, after which they reappear in the partially decalcified Broken Beds. The temporary disappearance of celestine–calcite rock may be due partly to a deterioration of the exposures, and partly to dipping of the base of the breccia below the level of the beach. It is unlikely, however, that the celestine was ever continuous.

Below the Broken Beds immediately north of fault F.3 the Soft Cap is rich in celestine. The mineral is mainly confined to the lower half (Fig. 1, C.3) of the division and, although occurring south of the fault, it is abundant only to the north. The celestine is concentrated both in the form of thin beds traceable over several square yards and as lenticles a few inches long. Less conspicuously a considerable proportion is present distributed throughout the limestone. Probably the celestine content is greatest where the bed dips below the level of the beach.

3. THE PETROLOGY OF THE CELESTINE–CALCITE ROCK

(a) General

The celestine–calcite rock from Durlston Head is grey or white in colour, with a weathered surface that shows a network of celestine crystals standing out in relief. Sometimes the bedding is poorly displayed by variation in the celestine content, usually about one third by weight, or by variation in celestine crystal size. Present in the upper celestine bed are contortions of a type that are also present in the subjacent limestone of the Broken Beds.

The celestine crystals, which never display the well-known blue tint, are characteristically tabular in habit, showing development of the basal pinacoid, macrodome, brachydome and prism faces. Elongation is parallel to the b crystallographic axis. A marked feature, especially in the upper bed, is the large proportion of bent and broken celestine crystals (Fig. 3). Bending, the more common phenomenon, ranges from gentle flexure to folds of ninety degrees or more; in a few cases the appearance of fracture may be due to solution and replacement by calcite at the geniculation.

The incomplete matrix is composed of anhedral calcite with an average grain size of about 0.1 mm., and enclosing scattered anhedral celestine crystals of similar size. Narrow veins of calcite, consisting of spherulites approximately 0.5 mm. in diameter, cut through the rock, and adjacent to these veins similar fibrous calcite sometimes forms the matrix. When examined macroscopically, this type of rock presents a much darker and more compact appearance.

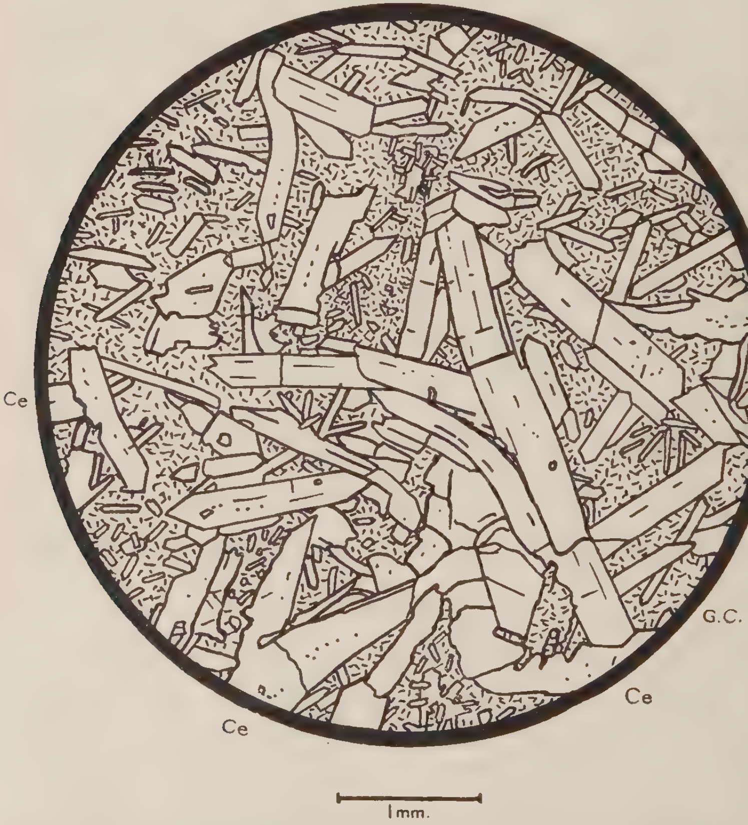


Fig. 3. Typical celestine--calcite rock from the upper celestine bed, Durlston Head. Predominantly euhedral celestine crystals (Ce), some bent and others partly replaced by calcite at their margins, in a matrix of fine-grained calcite (G.C.) with some minute celestine crystals. Ordinary light, calcite stained

(b) Replacive Processes

(1) Several stages in the development of pseudomorphs can be seen in the calcite veins. Celestine replaces adjacent parts of several calcite spherulites, ultimately to form anhedral celestine crystals. Early stages consist of groups of celestine fibres, the long axis orientation of which is determined by the spherulites (Fig. 4). Later, due to recrystallisation, single crystals of celestine enclosing radial calcite fibres as inclusions are formed.

In all cases the relatively late arrival of the secondary celestine is indicated by its greater abundance towards the centre of the veins. Probably it results from solution of some of the original euhedral celestine,

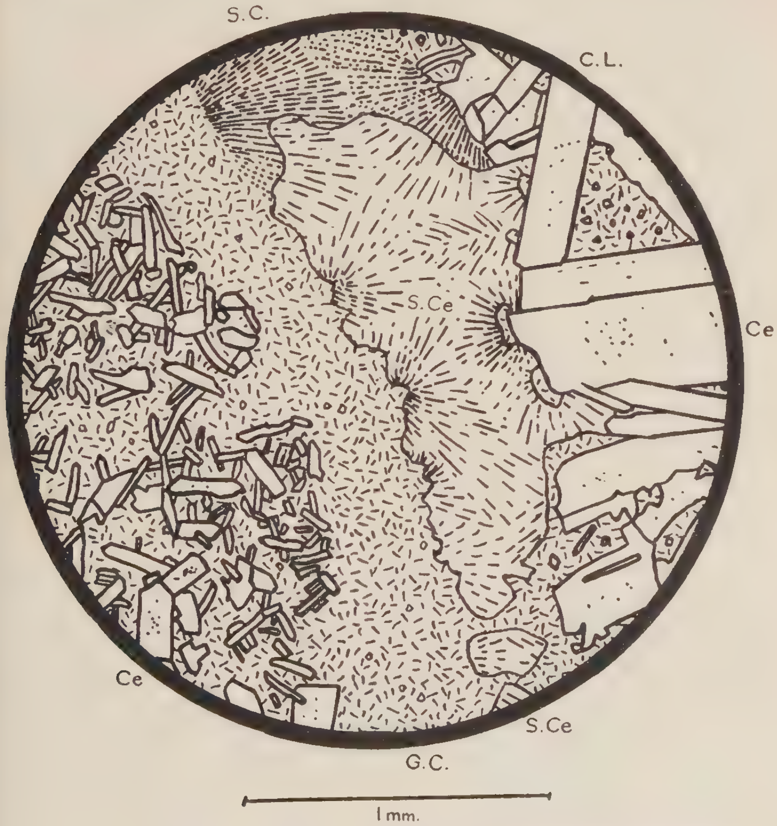


Fig. 4. Vein of spherulitic calcite (S.C.) partly replaced by spherulitic celestine (S.Ce) and on one side granular calcite (G.C.) similar to the matrix of euhedral celestine (Ce) which the vein cuts. The difference in grain size of the celestine on either side of the vein is due to a minute degree of faulting

the individual crystals of which are often cut and slightly displaced by the calcite veins.

(2) Another form of replacement, the reverse of that described above, is the partial or complete substitution of celestine by calcite. This is very common in parts of the celestine beds, and reaches a climax a hundred yards north of the main exposures where blocks of limestone, composed almost entirely of such pseudomorphs, occur in the partially decalcified Broken Beds.

There much anhedral celestine is found in the matrix of the breccia with euhedral secondary celestine in the cavities. Both these forms of celestine have probably been removed from the blocks by solution, when replacement took place within them. The fact that bending had sometimes occurred prior to replacement may also indicate that the replacement postdated brecciation.

(3) A third form of replacement is suggested by the occurrence of occasional irregular patches of quartz 0.1–0.2 mm. in diameter, usually showing a reticulate pattern of faint lines. This closely resembles in shape the boundaries of the anhedral calcite crystals in the matrix. Less commonly the form of the quartz resembles sections of celestine crystals, but undoubted evidence of quartz replacing celestine has not been seen.

(c) Composition of the Celestine

The celestine crystals appear to be composed entirely of strontium sulphate, no barium having been detected in a paper chromatographic separation of a solution prepared from them. Absence of barium was also confirmed optically by measurement of 2V, which was determined as (+) 50°. The chromatographic separation and optical determinations were carried out by M. E. Cosgrove.

4. CONDITIONS OF DEPOSITION

Some writers, notably Twenhofel (1939), maintain that nearly all deposits of celestine are of epigenetic origin. The only point in favour of such an origin for the Durlston Head occurrence is the apparently small lateral extent of the celestine-bearing rock. However, this is rather doubtful since the lower bed, still rich in celestine, dips below beach-level about fifty feet north of the fault F.3 (Fig. 2). The fault plane (F.3) offers no explanation of any vertical control, for the evidence suggests that the celestine antedates the local disturbances. The evidence may be summarised as follows:

(1) The upper celestine bed is involved in the Broken Beds and these are displaced by faults.

(2) Some veins of celestine pass downwards from both celestine beds and,

where these penetrate drag folds, they are displaced by the adjustment movements of the laminae involved.

(3) Celestine occurs in the fault plane only where the celestine beds are cut. Calcite is the predominant mineral here.

A syngenetic origin for the celestine is suggested by the predominantly euhedral form of the celestine crystals and the restriction of the mineral to certain definite horizons not otherwise lithologically dissimilar from the containing sequence. In the lower bed, however, celestine is present not only as thin bands, but also as lenticles a few inches in diameter, above and below which the bedding appears to split and pass. Richardson (1921) considered that concretions of such a form are almost invariably due to growth in, and displacement of, the surrounding material. Twenhofel, referring to this conformity between bedding planes and surfaces of concretions, thought that two modes of origin are possible. He stated (1939, 548) 'this may take place in concretions of epigenetic origin that develop between beds and in syngenetic concretions because of the settling of the beds between and around them'.

A replacement origin for the celestine in the lower bed is clearly impossible unless the original material was itself in the form of a concretion. Bearing in mind the form of the crystals, the occurrences of thin shaly laminae towards the periphery, and the ill-defined transition into the surrounding limestone, a syngenetic origin of the concretions appears the more probable of the two alternatives.

Although celestine occurs, in small quantities, in deposits of very diverse origins, when syngenetically deposited it is not uncommonly associated with gypsum. It occurs thus associated in Jurassic lacustrine sediments of California (Murdock & Webb, 1940). Celestine is worked in the Yate district near Bristol where it appears to lie on the horizon of the Newark Gypsum (Sherlock, 1915), although the two minerals are rarely present together.

Gypsum is present in the Lower Purbeck Beds of Durlston Bay where it occurs in the Soft Cockle Beds, a higher horizon than the Broken Beds. The hypothesis of Hollingworth (1938) that anhydrite or gypsum was once present in the Broken Beds suggests the possibility that the deposition of the celestine took place in a similar manner to that suggested for the Yate celestine (Sherlock, 1938). River water flowing from the west, the direction of the Purbeck shoreline (Arkell, 1933), may have derived strontium from the celestine-bearing Triassic rocks of the West of England, and on mixing with calcium sulphate saturated water, precipitated the celestine. Freshwater fossils occurring in the Caps and Broken Beds farther west and thick evaporite deposits at the base of the Purbeck Beds to the east, at the Portsdown boring (Lees & Cox, 1937), give support to this view.

5. TECTONIC HISTORY

The fault pattern, shown in Fig. 2, indicates a vertical maximum stress. This strictly local phenomenon probably owes its origin to the two major normal faults shown in Strahan's Durlston Bay Cliff Section (1898, fig. 122, 92) at Durlston Head which, higher in the cliff, downthrow a trough of Middle Purbeck Beds. The southern fault, a continuation of F.1 in Fig. 2, forms the southern boundary of the disturbed area while the northern one, although affecting the higher horizons, has not faulted the beds at the base of the cliff (Strahan, 1898). Thus, at this point, the Lower Purbeck Beds have been forced to occupy a lesser thickness than they do immediately north, and have necessarily been subjected to a high vertical pressure. Lateral movement consequently has resulted. To some extent this has taken place along an east–west direction as is evidenced by nearly horizontal slickensides on the plane of fault F.3. All other movement, as indicated by slickensides on the other faults, drag folds under the Soft Cap and Broken Beds north of fault F.3, and the trend of tectonic pseudoripples at the top of the Soft Cap, has been south to north. Southward thinning and northward thickening of the Broken Beds and the Caps, and southward inclination of the axial plane of the minor syncline at its base above the Soft Cap (Fig. 2), all suggest northward movement.

Most of the evidence of northward movement is present in that part of the section where the celestine occurs, and this also shows Broken Beds that are not fully brecciated. This is unlikely to be a coincidence for there are no other sections showing unbrecciated strata of this horizon in the Swanage district. Instead, the squeezed condition probably resulted from abnormally high vertical pressure. Accepting tectonic processes as the main cause of the Broken Beds, brecciation under these conditions may have been prevented while sliding or imperfect plastic flow took place instead.

Furthermore, as is considered above, the original presence of soluble evaporites is not unlikely. Local abundance of these adjacent to the celestine deposits could explain the remarkable thinning of the Broken Beds between faults F.1 and F.3, and the degree of response of such strata to a tectonic stress. The production of considerable faulting and folding in gypsum deposits by small tectonic forces has been described recently from the Upper Permian Marls of Ripon Park, Yorkshire (Forbes, 1958), where, it may be noted, celestine has also been detected.

Since the faults at Durlston Head trend parallel to the axis of the Purbeck Anticline, these disturbances were presumably Tertiary in age, and probably followed not long after the brecciation of the Broken Beds.

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REFERENCES

ARKELL, W. J. 1933. *The Jurassic System in Great Britain.* Oxford.

———. 1938(a). Three Tectonic Problems of the Lulworth District: Studies on the Middle Limb of the Purbeck Fold. *Quart. J. geol. Soc. Lond.*, **94,** 1–54.

———. 1938(b). The Purbeck Broken Beds. *Geol. Mag.*, **75,** 333–4.

———. 1940. Dorset Geology, 1930–40. *Proc. Dorset nat. Hist. Fld Cl.*, **61,** 117–35.

———. 1947. The Geology of the Country around Weymouth, Swanage, Corfe and Lulworth. *Mem. geol. Surv. U.K.*

BRISTOW, H. W. 1857. *Vertical Sections of the Geological Survey.* Sheet No. 22.

———. 1859. *Horizontal Sections of the Geological Survey.* Sheet No. 56.

DAMON, R. 1860. *Geology of Weymouth, Portland and the Coast of Dorset.* Stanford, London.

FISHER, O. 1856. On the Purbeck Strata of Dorsetshire. *Trans. Camb. phil. Soc.*, **9,** 555–81.

FITTON, W. H. 1836. Observations on some of the Strata between the Chalk and the Oxford Oolite in the South-East of England. *Trans. Geol. Soc., Series II,* iv, 103–388.

FORBES, B. G. 1958. Folded Permian Gypsum of Ripon Park, Yorkshire. *Proc. Yorks. geol. (polyt.) Soc.*, **31,** 351–58.

FORBES, E. 1850. On the Succession of Strata and Distribution of Organic Remains in the Dorsetshire Purbecks. *Rep. Brit. Ass.* for 1850, 79–81.

HOLLINGWORTH, S. E. 1938. The Purbeck Broken Beds. *Geol. Mag.*, **75,** 330–2.

LEES, G. M. & P. T. COX. 1937. The Geological Basis of the Present Search for Oil in Great Britain. *Quart. J. geol. Soc. Lond.*, **93,** 156–87.

MURDOCK, J. & R. W. WEBB. 1940. Notes on some Minerals from Southern California. *Amer. Min.*, **25,** 549–55.

RICHARDSON, W. A. 1921. The Relative Age of Concretions. *Geol. Mag.*, **58,** 114–24.

SEDGWICK, A. & R. Murchison. 1840. On the Physical Structure of Devonshire. *Trans. Geol. Soc., Series II,* v, 633–703.

SHERLOCK, R. L. *et al.* 1915. Gypsum and Anhydrite. Celestine and Strontianite. *Mem. geol. Surv. U.K.* 1st ed.

———. 1938. ibid. 3rd ed.

STRAHAN, A. 1898. The Geology of the Isle of Purbeck and Weymouth. *Mem. geol. Surv. U.K.*

TWENHOFEL, W. H. 1939. *Principles of Sedimentation.* New York.

WEBSTER, T. 1816. *Letters from Dorset.* (In Englefield H.C. *Picturesque Beauties of the Isle of Wight.* 117–238.)

———. 1826. Observations on the Purbeck and Portland Beds. *Trans. Geol. Soc., Series II,* ii, 37–44.

WOODWARD, H. B. 1895. The Middle and Upper Oolitic Rocks of England (Yorkshire excepted). *Mem. geol. Surv. U.K.*

Differential Growth in Carboniferous Brachiopoda

by D. PARKINSON

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ABSTRACT: It is shown by biometric studies of a number of British species that changes in the specific growth constants are often a necessary consequence of allometric growth. Support is given to the concept of allometry as a biological principle. Retardation in evolutionary trends by allometric changes is demonstrated.

1. INTRODUCTION

IN THE delimitation of fossil species variability in form and characteristics of growth are features of importance which should be taken into consideration whenever possible. This can only be the case when sufficient material is available for examination. A few specimens (or even one) might serve for a diagnosis, but it is evident that a more reliable assessment is possible with large samples than with small ones.

Apart from the value of variation and growth studies as an aid to species discrimination, such studies are important in their own right. In the present paper relative growth in brachiopods is treated as an end in itself, the species dealt with being employed in an illustrative sense. With one exception—*Brachythyris ovalis* (Phillips)—these forms have been described and figured in recent years (Bond, 1941; Muir-Wood, 1951; Parkinson, 1952, 1954).

2. GENERAL CONSIDERATIONS OF RELATIVE GROWTH

In the case of a living animal differential growth between its parts, e.g. between the length of a limb and the total length of the animal, can be estimated by measurements made at intervals during the period of growth. In the case of fossils growth lines or other indications of changing size and shape in a single individual might give relative growth information as has been shown by Westoll's study of *Dielasma elongata* (Zuckerman *et al.*, 1950, 491). Where such treatment is inapplicable a biometrical approach can be made, assuming that a sufficient number of individuals can be measured and that their size is a sufficiently close approximation to their age. Brachiopods grow throughout life and lend themselves to statistical methods of growth analysis. In attempting to study the growth of an individual by averaging over a population it must be remembered that any sharp discontinuities in the growth rate will be smoothed out.

Among those who have studied relative growth, Julian Huxley (1924, and other publications) may be mentioned in particular. In stressing the importance of the allometric equation

$$y=\beta\, x^{\alpha} \text{ (also written } y=b\, x^{\alpha} \text{ and } y=b\, x^{k})$$

he has pointed out that most animals reach their adult size and shape by relative growth in different directions in accordance to a first approximation with this formula in which y represents the size of some part of the organism and x either the whole body or some part of it selected as standard. β and α are constants.

The physical meaning of this equation is that a part of the organism will grow in proportion to some constant power of the size of the whole. The constant β represents the value of y when $x=1$ and its value is dependent on the units in which x and y are measured. The exponent α represents the ratio of the specific or logarithmic growth rates and is referred to by Huxley as the coefficient of relative growth, or in cases where size allometry is regarded as a measure of differential growth as the growth-partition coefficient (Zuckerman *et al.*, 1950, 466). In allometric growth the specific growth rates of x and y are unequal and generally vary with age, but their ratio α remains constant.

When the exponent α is greater than unity, allometric growth is positive; when it is less than unity it is negative. In the special case when $\alpha=1$ the growth is isometric, i.e. there is no change in the proportion of the parts of an organism with increase in its absolute size.

Graphically, isometric growth is represented by a straight line on arithmetical co-ordinates, whereas for allometric growth linearity is shown on a double logarithmic grid or by plotting the logarithms of x and y on an arithmetical grid since $\log y=\alpha \log x+\log \beta$.

The significance of the allometric growth equation has been the subject of much discussion (see in particular Zuckerman *et al.*, 1950). The law as simply expressed is rarely ever precisely realised throughout the growth of the animal (or plant). In many cases the values of the parameters α and β change during growth and linearity can only be shown by splitting the data into two or more segments. Moreover, the equation ignores the fact of time (size is assumed to be a function of time or age) and refers only to relative size. Discussion has largely centred on the question as to whether the allometric formula has the status of a biological law or should be regarded as merely empirical. Huxley, although he has stressed its shortcomings, argues that it is a valid principle (Zuckerman *et al.*, 1950, 465) following the supposition '(a) that the growth involved is essentially multiplicative, depending on the progressive self-multiplication of some unit or units, (b) that different parts of the body differ in multiplicative rate, i.e. in specific growth rate, (c) that some factor operates to keep the ratio of specific growth rates between various parts a constant one'.

An objection to the allometry equation as expressing a biological or physiological law has been raised by Waddington (*in* Zuckerman, 1950, 511) among others on the grounds of the formal properties of the equation that if two different parts of an organism have an allometric relation to the whole they cannot have it to one another. Waddington, for this reason and because 'in many cases the equation can only be fitted by invoking a series of sudden changes in the constants, so as to fit a number of straight lines to data which would more naturally be described by a curve' regards it as no more than a rough-and-ready method of description.

Huxley (1950, 466) does not accept this view, arguing from the large number of cases of quite different kinds of organs showing approximation to allometric growth that some principle must be involved. He suggests that some second order factor prevents the allometric formula from ever being precisely realised and hints at the possibility that 'the increasing relative size of a part attained as a result of a high relative growth rate might have a slight inhibitory effect on the growth rate itself'.

Medawer (*in* Zuckerman *et al.*, 1950, 477), in support of Huxley, points out that the growth of an organism being fundamentally of the multiplicative type makes it expedient to use the specific growth rate to describe the course of growth as a function of age. He then shows mathematically that the *ratio* of specific growth rates is justifiably used to describe the differential growth of two parts. He further points out that 'the ratio of two specific growth rates is an acceptable formulation of differential growth even if their ratio is inconstant'. He deals with the objection that some kinds of growth are accretionary and not multiplicative by instancing cases where accretionary growth is subsidised by multiplicative growth systems.

3. DIFFERENTIAL GROWTH IN BRACHIOPODS

The writer's studies of Carboniferous brachiopods, published and unpublished, has shown that the allometric formulation holds in cases of relative growth between different parts of the shell. For the length–width relationship growth is often very nearly isometric; this applies in particular where the two valves are approximately equal in length and breadth. Isometric growth is less common for the thickness–width and thickness–length relationships, but it sometimes fits the data reasonably well.

Where the shells attain a size exceeding some twenty-five to thirty millimetres a single straight line can often not be drawn through the centre of a scatter diagram relating the different parts. In such cases satisfactory formulations can usually (though not invariably) be found by analysis of the data in two segments, giving two allometric equations involving a change in the values of the parameters α and β.

The best standard of reference for relative growth studies of brachiopods is the width of the shell, which is of course the width of both valves. The total length can alternatively be taken, but this involves only one valve, usually the pedicle valve; though sometimes the brachial valve is the longer of the two. Moreover, it has been shown in the case of *Dielasma hastata* (Parkinson, 1952) that the width is more closely related to the volume of the shell than is either the length or thickness.

It is hoped to show in this paper that changes in the relative growth constants between the different parts of brachiopod shells are normally to be expected. The following considerations will have a bearing on the argument:

When growth is allometric there will sometimes be a value where the two variates are equal. At the stage when $y=x$ we can put $\log y=\log x$ in the allometric equation $\log y=\alpha \log x+\log \beta$

$$\text{and hence } \log x=\alpha \log x+\log \beta=\frac{\log \beta}{1-\alpha}$$

Where two characters y and z are related to x independently there will sometimes be a value where $y=z$ at a fixed value of x.

At this value we can put $\log y=\log z$ in the equations

$$\log y=\alpha \log x+\log \beta$$

$$\log z=\alpha_1 \log x+\log \beta_1$$

$$\therefore \alpha \log x+\log \beta=\alpha_1 \log x+\log \beta_1$$

$$\text{and } \log x=\frac{\log \beta_1-\log \beta}{\alpha-\alpha_1}$$

Graphical methods of obtaining these results are used in the following pages.

The data recorded in this paper have been analysed by the reduced major axis method described by Kermack & Haldane (1950) who have shown that the reduced major axis is invariate under a change of scale and impartial between x and y. The procedure is simpler than regression analysis, and, what is more important, gives a straight line through the scatter which is better representative of the relation between the two variates in cases such as we are now considering when neither variate can be regarded as the independent one. (See also Kermack, 1954; Imbrie, 1956; Prentice, 1956; and Sylvester-Bradley, 1958.)

In the work described in this paper the measurements of the shell, total length = L, width = W, thickness = T and depth = D have been made in the conventional directions (Figs. 1 and 4).

4. RELATIVE GROWTH CHARACTERISTICS OF SOME BRACHIOPOD SPECIES

(a) Brachythyris ovalis (Phillips)

Measurements have been made on 41 specimens from the *Dielasma* bed of the Lower *Dibunophyllum* Zone (D_1) at Treak Cliff, Derbyshire (Fig. 1), of a form apparently referable to *B. ovalis*. The sample can be regarded as drawn from an interbreeding population since the specimens were all collected from an exposure a few inches thick and less than a yard in extent. This shell has its length and breadth substantially equal; in fact the simplest possible equation of the form $y = x$ is almost realised for the $L - W$ relationship as can be seen from Fig. 2, where the broken line (C) represents $L = W$. The fitted reduced major axis A has the equation $L = 0.916\ W + 1.031$. Relative growth between T and W is also isometric throughout, the fitted line $T = 0.590\ W - 0.354$ almost passing through the origin of the graph.

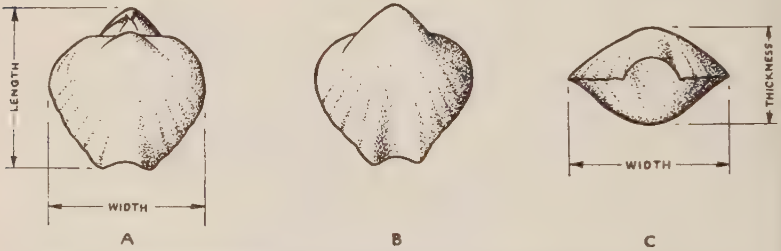

Fig. 1. *Brachythyris ovalis*. (A) dorsal view, (B) ventral view, (C) anterior view

It should be noted that isometry does not necessarily imply that the growth line passes through the origin, but if the intercept is significantly different from zero, the calculated equation will not hold in the very early growth stages and an allometric relation may be suspected.

Confirmation of isometry in this case is confirmed by plotting and analysing the logarithms, the equations being $\text{Log } L = 0.948 \log W + 0.055$ and $\text{Log } T = 1.030 \log W - 0.282$ in which the values of α do not differ significantly from unity.

(b) Pugnax pugnus (Martin)

Relative growth studies have been published on four samples of this species, representing in all some 1350 specimens. Allometric growth was shown in all cases of $L - W$ and $T - W$ without any changes in the values of

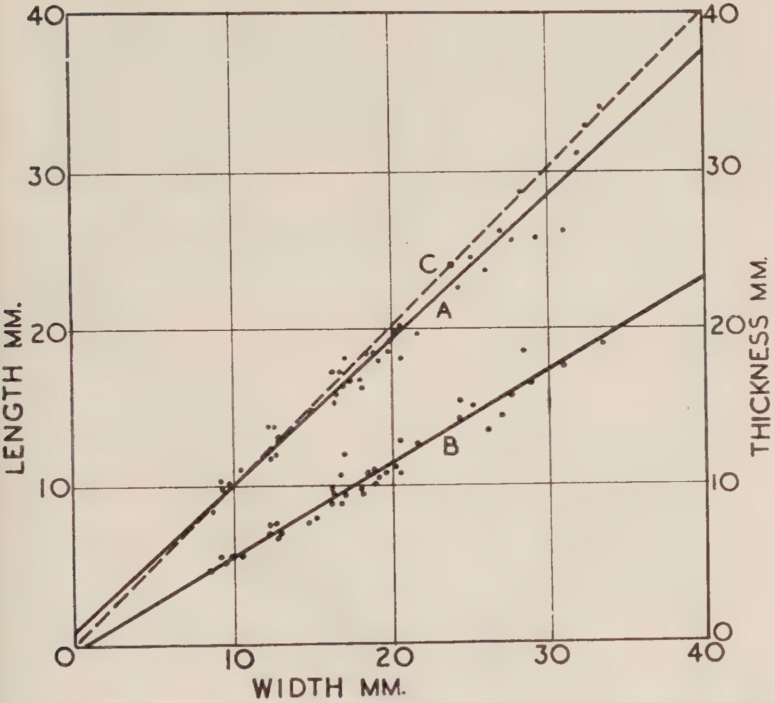

Fig. 2. Scatter diagrams illustrating isometric growth of *Brachythyris ovalis*. A and B are the reduced major axes for the equations $L=0.916\ W+1.031$ and $T=0.590\ W-0.354$ respectively

the growth ratio α (Parkinson, 1954). The largest assemblage consisted of 829 measurable specimens from a pocket about nine feet thick in the D_1 reef limestone of Cave Dale, Castleton, Derbyshire. Scatter diagrams on log/log plots revealed homoscedasticity and linearity for $T-W$ and $L-W$, but the $D-W$ scatter curved towards the W axis in the later growth stages.

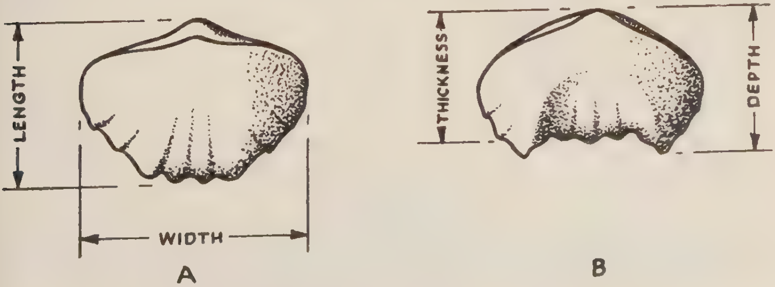

Fig. 3. *Pugnax pugnus*. (A) dorsal view, (B) anterior view

The depth D (Fig. 3) is the sum of the thickness measured through the middle of the shell perpendicular to the plane containing the length and width, and the depth of the broad sinus in the pedicle valve. Since this sinus does not develop in the earliest growth stages D has no real significance apart from T until it appears. In the more recent examination of the data now to be considered the $D-W$ scatter has been replotted (Fig. 4) excluding 130 specimens where $D=T$.

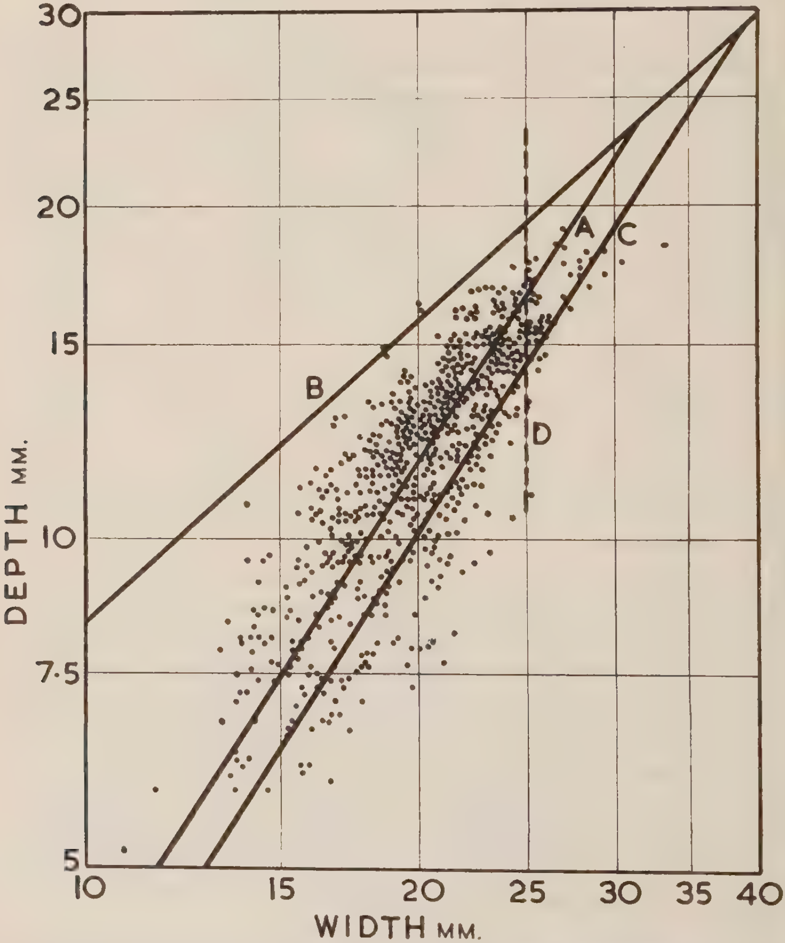

Fig. 4. Scatter diagram of $D-W$ (where $D>T$) for *Pugnax pugnus* from Cave Dale. A is the growth line (reduced major axis) for $D=0.112\ W^{1.552}$, excluding the scatter to the right of the broken line D. The growth lines B and C represent $L-W$ and $T-W$, the equations to which are $L=1.021\ W^{0.912}$ and $T=0.097\ W^{1.554}$ respectively

In Fig. 4 the reduced major axes B and C represent the equations Log $L=0.912 \log W+0.009$ and Log $T=1.554 \log W-1.014$ respectively, which are given in the 1954 paper for the whole sample of 829 individuals. These lines meet at approximately 29 mm. on the y axis and 39 mm. on the x axis. (Calculation by the method outlined earlier gives 28.95 and 39.21 respectively.) This means by extrapolation that L and T will be equal in mean value at 29 mm. with W at 39 mm. It means further, that D, which is normally greater than T, will become equal to L at some value less than 29 mm. unless the allometric constants change. The bend in the $D-W$ scatter suggests in fact that such changes are already taking place. There is the further suggestion from the fact that the $D-W$ scatter inclines towards

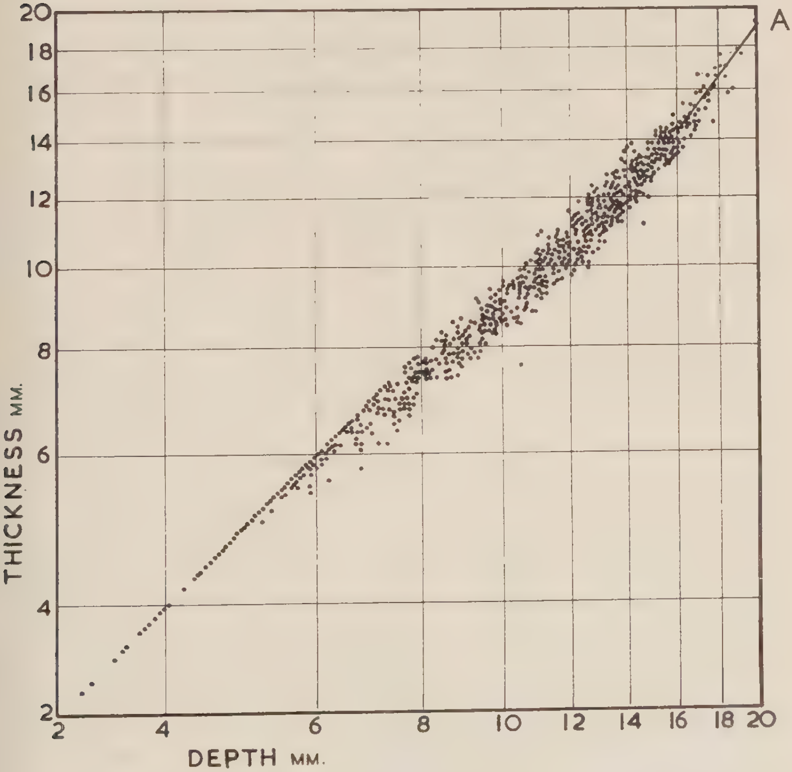

Fig. 5. Scatter diagram of $T-D$ for *Pugnax pugnus* from Cave Dale, illustrating the changes in differential growth and the depth of the sinus in the pedicle valve. This appears at about 5 mm. T and increases rapidly in depth; the rate of increase then declines. The allometric growth line for the 50 specimens deeper than 16 mm. has the equation $T=0.370\ D^{1.313}$, which indicates a shallowing of the sinus in the larger specimens, i.e. T is approaching D in magnitude

the $T-W$ growth line that at a width of about 25 mm. the depth begins to decrease in relation to the thickness.

A plot (Fig. 5) was therefore made of the $T-D$ scatter. This diagram indicates that allometric relations can only be made by splitting the curve into a number of segments in which α, obviously $=1$ at first, then becomes negative and is finally positive. We are concerned in particular with the upper part of the diagram, which shows a bend in the scatter at about $D=16$ mm. Analysis of the 50 points where $D>16$ gives the equation Log $T=1.313 \log D-0.432$ (or $T=0.370\ D^{1.313}$). The fitted line A passes centrally through the points and if produced would show $T=D$ at 24 mm. (The calculated value, putting $\log T=\log D$ in the equation, is the same.)

We can now look again at Fig. 4. If the points beyond the broken vertical line D drawn at $W=25$ mm. are ignored the scatter is seen to be homoscedastic and an analysis of the sample of 643 specimens seems justifiable. The equation is Log $D=1.552 \log W-0.950$, and the line fitted to the scatter meets the $L-W$ line at about $L=24$ and $W=31.5$ mm. (The calculated values are $L=23.70$ and $W=31.48$.) Thus D would have become equal to L at 24 mm. with W at 31.5 mm. had there been no change in the growth constants. As we have seen $L=24$ is also the point at which $T=D$.

Now according to Fig. 4, $T=L$ at 29 mm. at a width of 39.5 mm. Assuming the general shape of the shell does not change radically this means that a change in α either for $T-W$ or $L-W$, or both, would be expected if the shell were to grow to such a size, otherwise the thickness would become greater than the length and depth. (Specimens of *P. pugnus* from Craven and Michlow have almost attained these dimensions without pronounced change in the general shape of the shell.) Since there is no suggestion of bends in the $L-W$ and $T-W$ scatter diagrams (1954, 568, fig. 5, 569, fig. 7) it can be presumed that the growth changes would occur later than that for the curved $D-W$ scatter.

The above conclusions are based on a very large sample of 829 shells from a restricted horizon at one locality. That they are characteristic of the species in general is indicated by the data displayed by the composite Craven sample of 434 specimens collected by R. H. Tiddeman over a wide area of D_1 reef limestone. The $L-W$ and $T-W$ plots have been figured (1954, 569, figs. 6, 8), but the $D-W$ scatter was not published. It is recorded here (Fig. 6), together with the fitted lines of the $L-W$ and $T-W$ diagrams, the equations of which are (A) Log $L=0.955 \log W-0.035$ and (B) Log $T=1.273 \log W-0.631$ respectively. The $D-W$ scatter again bends towards the W axis for the later growth stages.

The 1954 paper recorded no significant difference between the values of α for Cave Dale and Craven Reef in the case of the $L-W$ plots, but a significant difference for $T-W$. The mean size of the Craven Reef sample is greater than that for the Cave Dale community, and this is reflected by the smaller number of specimens, 13 out of 434 (included in Fig. 6) compared with 130 out of 829, in which $D=T$. This large difference can be explained by the fact that T rarely equals D in shells >8 mm. D and that the number of specimens from Craven <8 mm. deep is only 21 compared with 197 from Cave Dale.

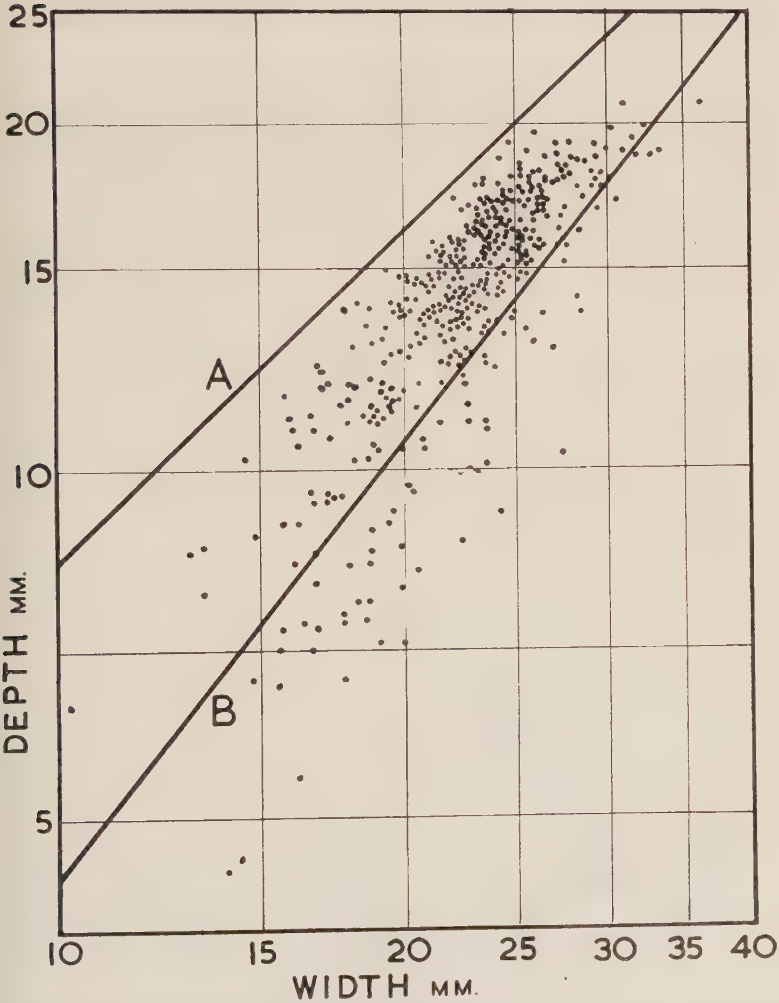

Fig. 6. Scatter diagram of $D-W$ for *Pugnax pugnus* from the Craven Reef belt. The scatter is curved as for Cave Dale. The lines A and B represent the straight scatters $L=0.923\ W^{0.955}$ and $T=0.234\ W^{1.273}$ respectively

An examination of the $D-W$ scatter from Craven Reef (Fig. 6) leads to similar conclusions to those of Cave Dale. An analysis of the $D-W$ scatter has not been attempted as it is more irregular than that of Cave Dale, but it is evident that but for the bend in it D would have become equal to L at a value not greatly exceeding that of the largest specimens measured. Mainly because α for $T-W$ is significantly less for Craven than for Cave Dale (1.273 compared with 1.554) T and L only coincide at 56 mm. with W at 75 mm.

(c) Pugnax pseudopugnus D. Parkinson

Relative growth data on this species were recorded (1954) on a sample of 39 specimens from the D_1 zone of Treak Cliff, Derbyshire, and on one of 855 specimens in the Tiddeman collection from D_1 of the Craven Reef

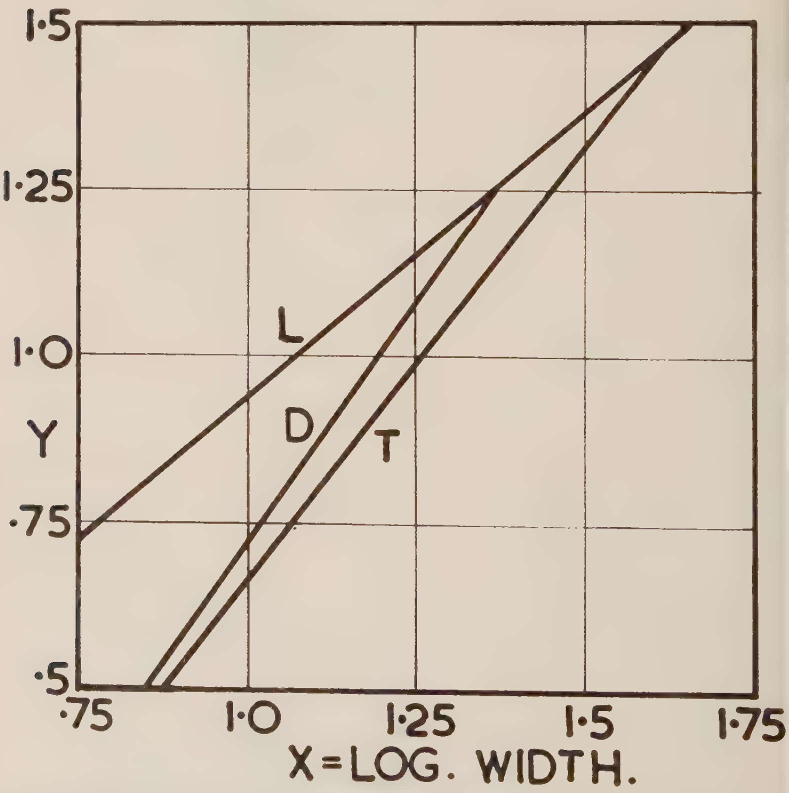

Fig. 7. Reduced major axes for *Pugnax pseudopugnus*, from Craven Reef. Y is the axis for logs L, D and T and X for log W. The equations are:
Log $L=0.855 \log W+0.087$, Log $D=1.422 \log W-0.698$ and Log $T=1.283 \log W-0.615$

Belt, Yorkshire. Scatter diagrams on log/log plots indicated linearity throughout growth for $L-W$, $T-W$, $D-W$ and $T-L$ and allometric equations were derived for the $L-W$ and $T-W$ plots. For the Craven Reef sample these are Log $L=0.855 \log W+0.087$ and Log $T=1.283 \log W-0.615$.

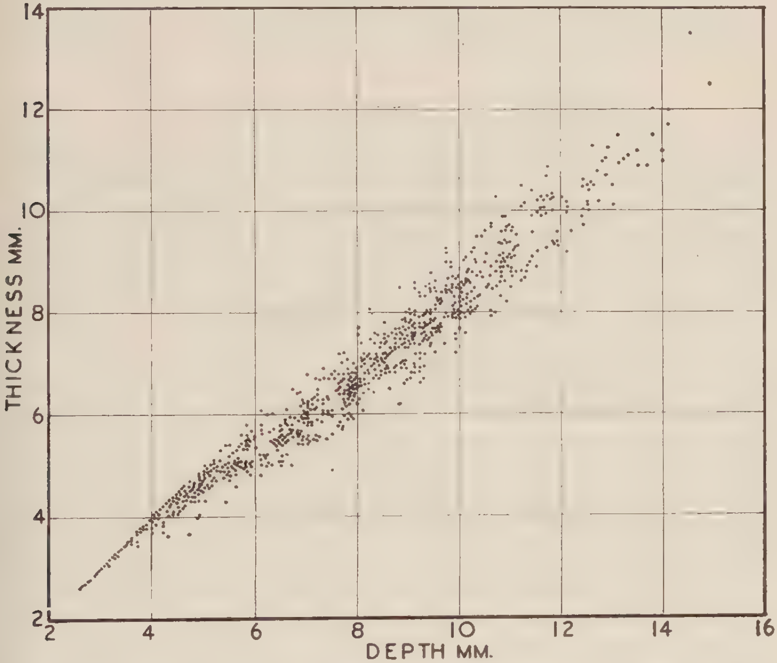

Fig. 8. $T-D$ relationship for *Pugnax pseudopugnus* from Craven Reef. As in *P. pugnus*, the sinus, after deepening in the earlier growth stages, shallows later

The following equations have since been worked out from the original data based on 772 specimens, i.e. those in which $D>T$: Log $D=1.422 \log W-0.698$ and Log $D=1.630 \log L-0.813$. In Fig. 7 the lines L, D and T represent respectively the equations relating L and W, D and W and T and W. They indicate that $D=L$ at about 19 mm. (antilog 1.28) with W at 24.5 (antilog 1.39). Calculation gives $D=L$ at 18.63 with W at 24.21. Also we find that putting $D=L$ in the equation Log $D=1.630 \log L-0.813$ a value of 19.50 is obtained for D and L. Similarly from Fig. 7, $T=L$ at about 30 mm. L and 43 mm. W.

Now the length of the longest specimen in the sample is 16.7 mm., only some 2 mm. less than the value at which the mean depth would be expected to equal the length, and therefore it would appear that the upper limit of size has been reached before the growth constants change. In fact such changes are already foreshadowed by the fact that D is decreasing relative to T in the larger individuals. A plot of $T-D$ follows a similar pattern to that for *P. pugnus*. It is here drawn on arithmetical co-ordinates (Fig. 8) and there is a suggestion of a slight break in the scatter at 12 mm. D. The 41 points greater than this value were drawn on a log/log plot (not shown). The equation to the fitted line is Log $T=1.400 \log D-0.527$, with $T=D$ at 20.8 mm.

(d) Pugnax acuminatus (J. Sowerby)

According to the writer's interpretation (1954), this is a very variable species, both in general shape and in the number of plications on the anterior margin. Specimens from several localities, totalling about 700, were measured. These were all found in reef limestone, either in the upper *Caninia* (C_2) Zone or Lower *Dibunophyllum* (D_1) Zone. The non-reef beds of the intervening *Seminula* Zone have not yielded any measurable specimens. Occasional individuals found in the bedded deposits of the D Zone are not easily removed from the matrix.

Allometric growth was found for $L-W$ and $T-W$, with changes in the values of α at about 25 mm. W in the samples from Thorpe Cloud, Derbyshire (C_2) and Narrowdale Hill, Staffordshire (D_1). Analyses were not made over the complete range in the other samples. The recent more comprehensive study has revealed new features of interest, both in differential growth itself and in its possible influence on the evolution of the species.

Of the many localities considered only one, at the top of Thorpe Cloud, has yielded an assemblage which can be regarded as forming part of an interbreeding population. The bed is a few yards in extent and one or two feet thick. Recent collecting has added to the number (93) previously analysed. The more recent analyses have been made on a sample of 114 individuals, including 43 with $W<25$ mm. and 71 with $W>25$ mm. The equations are, for $W<25$ mm., Log $L=0.939 \log W-0.015$ and

$$\text{Log } T=1.318 \log W-0.889$$

and for $W>25$ mm., Log $L=1.124 \log W-0.282$

$$\text{and Log } T=1.908 \log W-1.695$$

These equations differ little from those previously reported on the smaller sample, and the scatter diagrams again show the pronounced break at $W=25$ mm. Had there been no such break T would have become equal to L at about 140 mm. Following the changes in the values of α, $T=L$ at 50 mm. with W at 60 mm. This effect is opposite to that for *P. pugnus* and *P. pseudopugnus* where the changes in α increased the difference between T and L (and T and W) whereas for *P. acuminatus* they have decreased it, which at first sight seems to provide an unnecessary complication in the

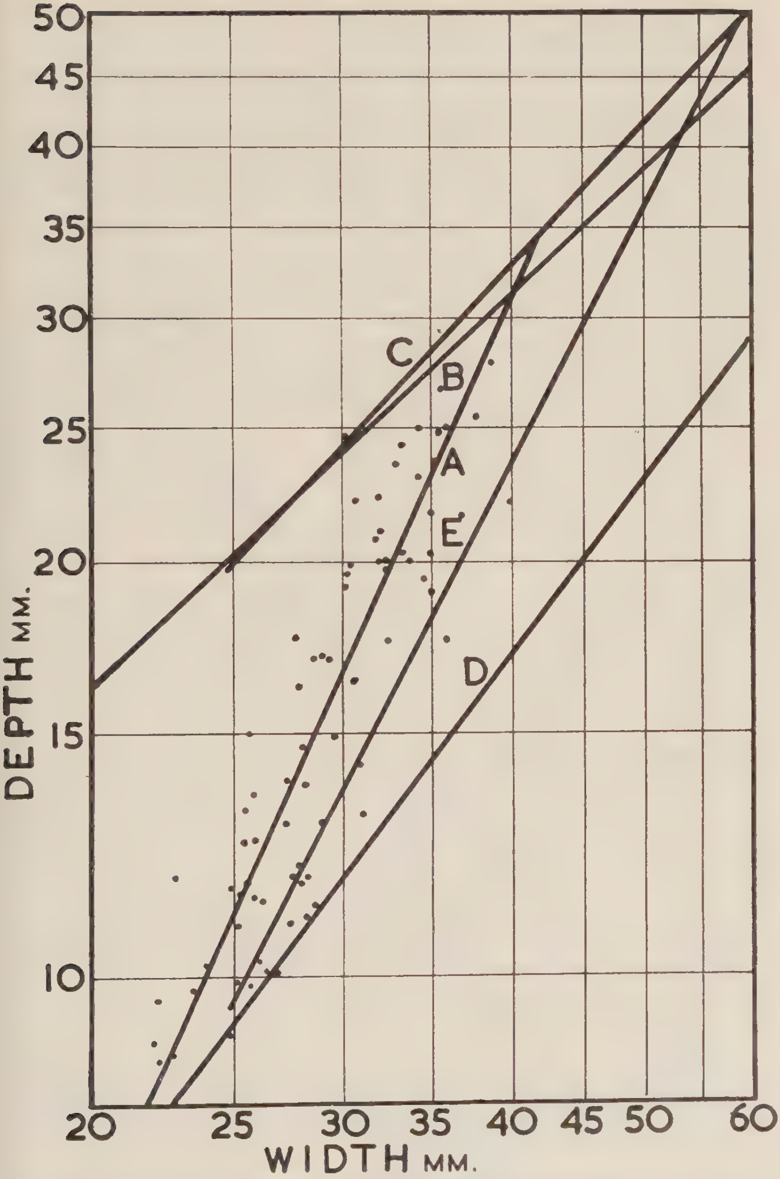

Fig. 9. Scatter diagram of $D-W$ ($D>T$) for *Pugnax acuminatus* from Thorpe Cloud with the reduced major axis A representing the equation $D=0.0084\ W^{2.218}$. B is the line for $L=0.966\ W^{0.939}$ ($W<25$ mm.); C represents $L=0.522\ W^{1.124}$ ($W>25$ mm.); D represents $T=0.129\ W^{1.318}$ ($W<25$ mm.); and E is the line for $T=0.020\ W^{1.908}$ ($W>25$ mm.)

growth characteristics. However, a consideration of the $D-W$ and $T-D$ scatter diagrams offers an explanation.

Up to 23 mm. W, the depth does not exceed the thickness, but once started the ventral sinus develops rapidly, with T being allometrically related to D without any change in α. Analysis of the 76 specimens where $D>T$ gives Log $T=0.828 \log D+0.131$ and Log $D=2.218 \log W-2.075$. The $D-W$ scatter is shown in Fig. 9, together with the fitted lines for this and the other relevant data. D is seen to become equal to L at about 35 mm.

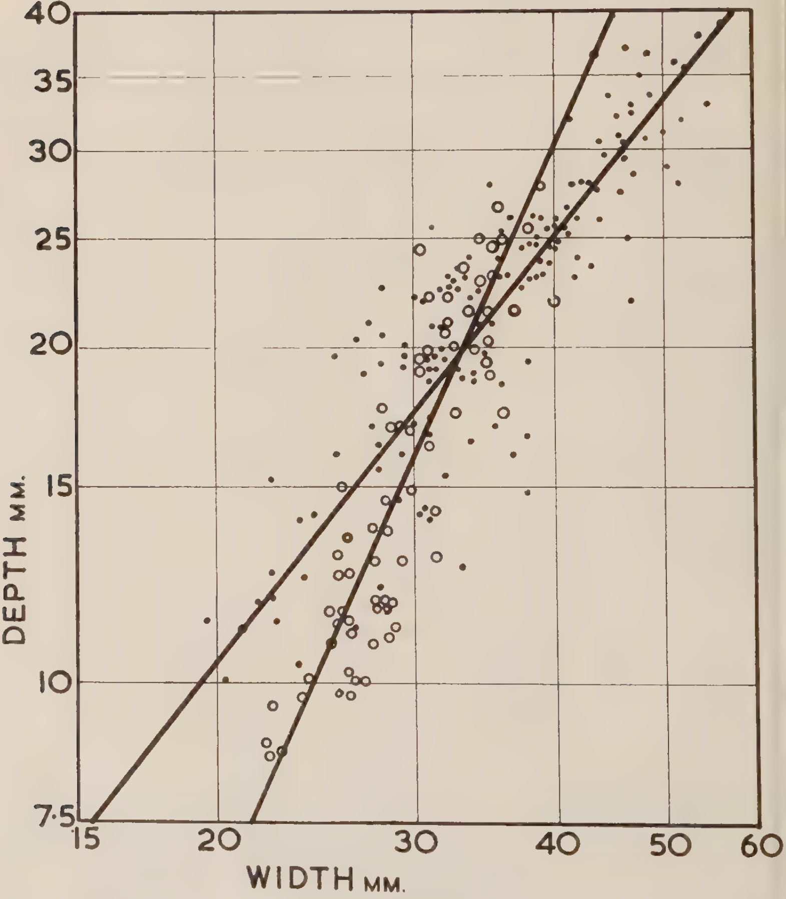

Fig. 10. The $D-W$ scatter diagram ($D>T$) for *Pugnax acuminatus*. The circles represent the Thorpe Cloud assemblage with the line $D=0.0084\ W^{2.218}$ and the dots the composite sample from the other localities in the C_2 Zone, with the line $D=0.228\ W^{1.279}$

(but for the change in α for $L-W$ it would have been at 30.5 mm.). At this value $T=25.75$. But for the change in α for $T-W$ it would have been about 18.25, a little more than half the value of D, which is uncharacteristic of the species.

Further consideration shows that still later changes in α would be expected if growth were carried much further. This follows from the fact that the longest specimen from Thorpe Cloud has $L=31.3$ mm. and $W=35.8$ and the broadest had $L=29$ mm. and $W=40$ mm., whereas $D=L$ at 34.5 mm. with W at 42.5 mm. Now much larger specimens of the species occur at Withgill, near Clitheroe, and Salt Hill, Clitheroe, and elsewhere in the C_2 Zone as can be seen from Figs. 10 and 11. In Fig. 10 the $D-W$ scatter (where $D>T$) for Thorpe Cloud is represented by circles and the combined scatter for other localities in the C_2 Zone by dots. Although the composite sample has a wide scatter there is no indication of curvature, and analysis of the 145 specimens other than those from Thorpe

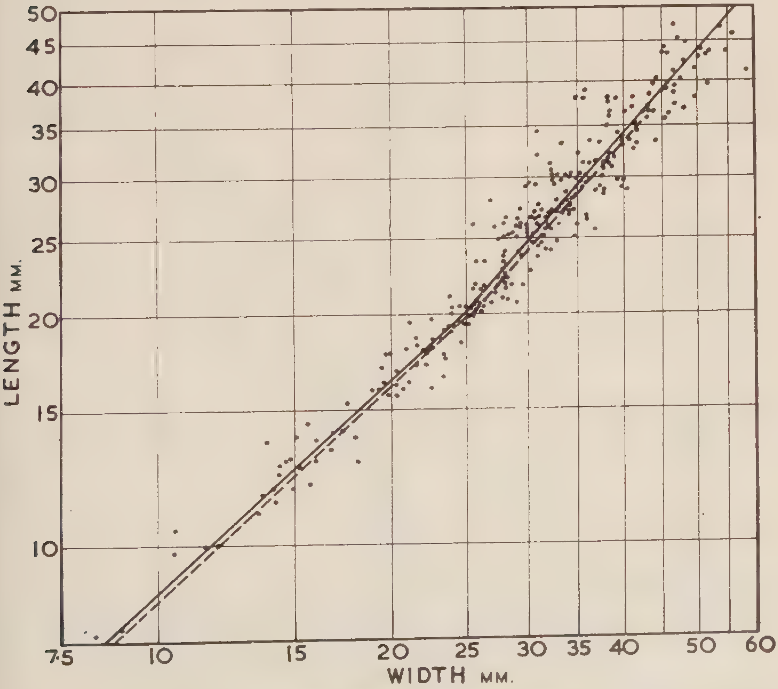

Fig. 11. Composite scatter diagram for all the measured specimens of *Pugnax acuminatus* from the C_2 Zone. The solid lines are the reduced major axes for the equations $L=0.995\ W^{0.935}$ and $L=0.556\ W^{1.115}$ respectively. The broken lines represent the Thorpe Cloud scatter, the equations being $L=0.966\ W^{0.939}$ and $L=0.522\ W^{1.124}$

Cloud gives the equation (for $D>T$) Log $D=1.279 \log W-0.642$. The fitted line for the Thorpe Cloud assemblage of 76 specimens intersects that for the combined sample at a fairly wide angle. The graph (Fig. 10) shows that 28 specimens of the composite sample exceed the depth of the deepest Thorpe Cloud specimen, and none of these is represented by points beyond the Thorpe Cloud growth line. The inference is that not only is a change in α for $D-W$ in the Thorpe Cloud community probable in the region of 30 mm. D and 40 mm. W, but that it is likely to be a drastic one (from 2.218 to <1.5). A corresponding change would be expected in the $T-W$ equation.

A similar change in the $L-W$ relation at about $W-40$ is unlikely, as is indicated by Fig. 11 which produces the $L-W$ scatter for the 284 measured

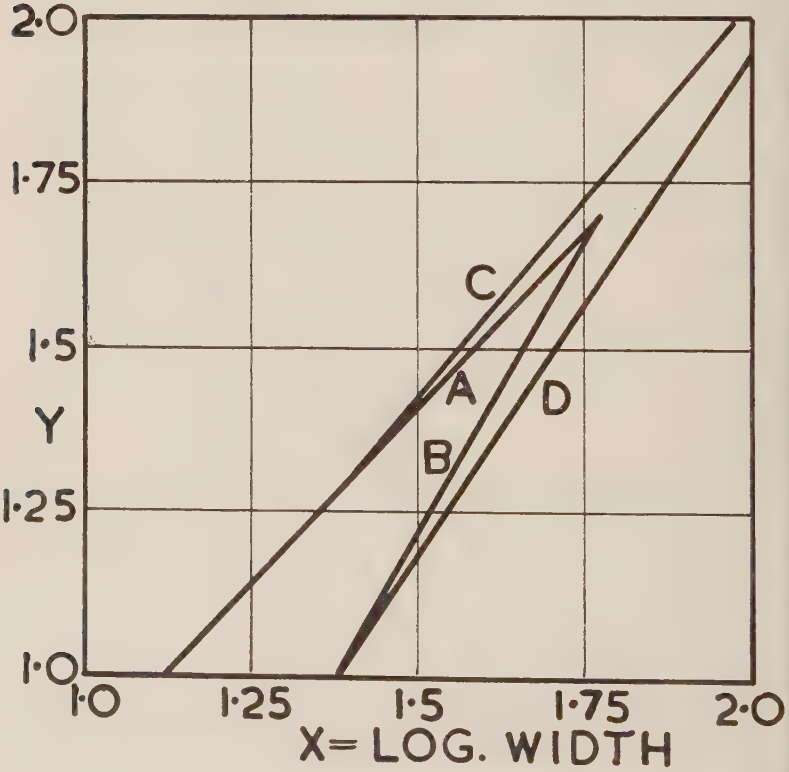

Fig. 12. Growth lines for the Narrowdale collection of *Pugnax acuminatus*. Y is the axis for logs L and T and X for log W. The equations are (for $W<25$ mm.) Log $L=1.060 \log W-0.183$ (A) and Log $T=1.799 \log W-1.477$ (B), and (for $W>25$ mm.) Log $L=1.209 \log W-0.395$ (C) and Log $T=1.525 \log W-1.098$ (D)

specimens from the C_2 Zone (including those from Thorpe Cloud).[1] The equations for the fitted lines are, for $W<25$ mm. $\text{Log } L=0.935 \log W-0.002$ and for $W>25$ mm. $\log L=1.115 \log W-0.255$. These do not differ appreciably from those of Thorpe Cloud, which are represented in Fig. 11 by the broken line. This indicates that Thorpe Cloud for the $L-W$ relation (unlike those for $T-W$ and $D-W$) is typical for the species as a whole as exemplified by the *Caninia* Zone collections.

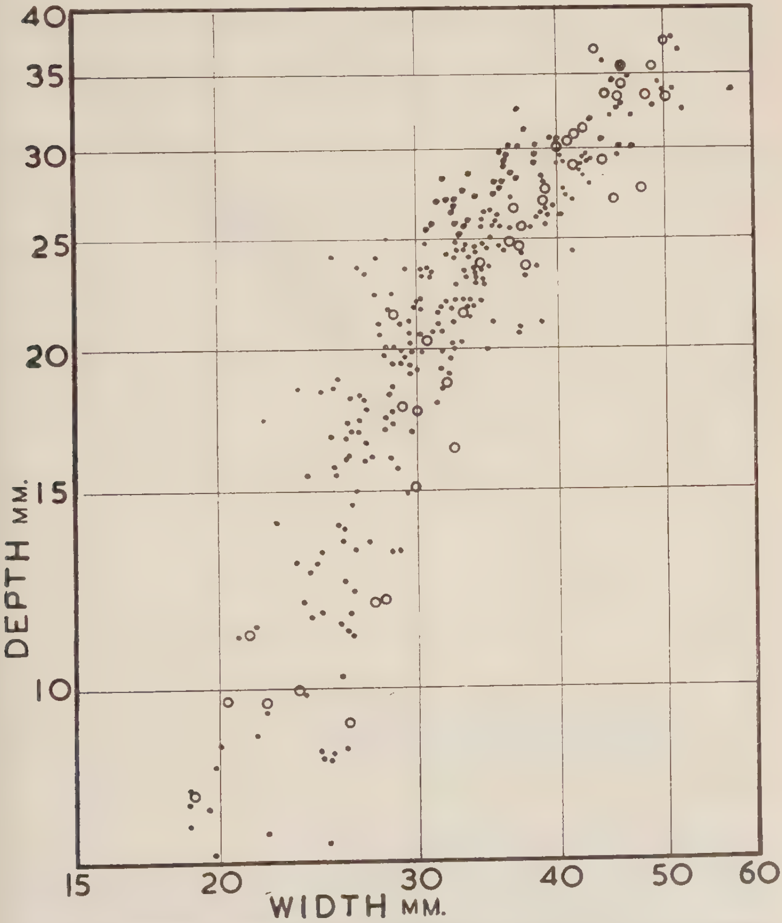

Fig. 13. $D-W$ scatter diagram for *Pugnax acuminatus*, D_1 Zone. The circles represent the Narrowdale sample and the dots the combined sample from the other localities

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[1] A large number of specimens from Bolland in the British Museum (Nat. Hist.) are excluded from the analyses, because there is some uncertainty of their age. However, their biometrical characters strongly suggest the C_2 Zone.

We can now consider the *Dibunophyllum* Zone collections, beginning with Narrowdale. The $L-W$ and $T-W$ equations given below are taken from the 1954 paper:

$$W<25 \text{ mm. } \log L=1.060 \log W-0.183$$
$$\log T=1.799 \log W-1.477$$
$$W>25 \text{ mm. } \log L=1.209 \log W-0.395$$
$$\log T=1.525 \log W-1.098$$

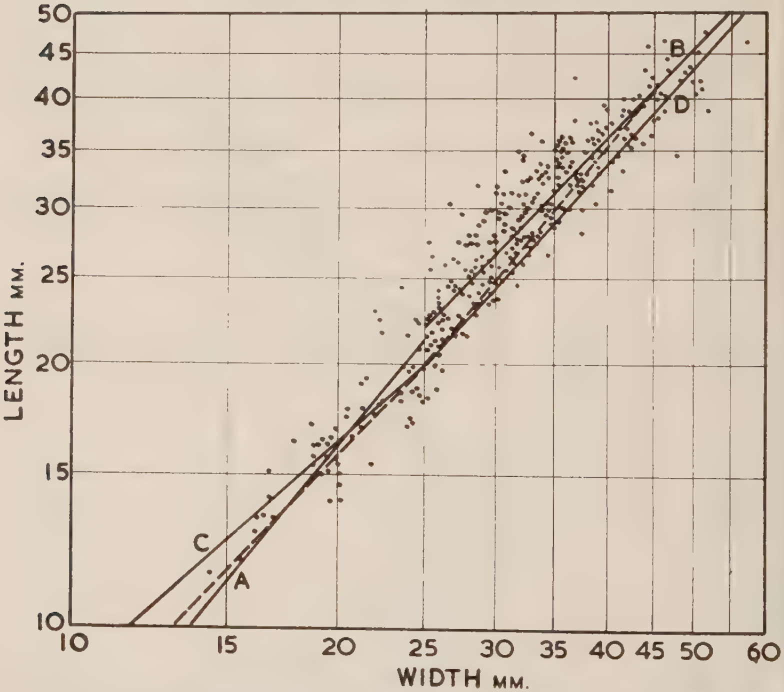

Fig. 14. $L-W$ composite scatter diagram for *Pugnax acuminatus*, D_1 Zone, with growth lines A and B representing the equations $L=0.401\ W^{1.233}$ and $L=0.713\ W^{1.064}$ respectively. The broken lines $L=0.656\ W^{1.060}$ and $L=0.403\ W^{1.209}$ are for Narrowdale. Lines C and D represent the C_2 Zone scatter ($L=0.995\ W^{0.935}$ and $L=0.556\ W^{1.115}$)

There are again breaks in the diagrams at 25 mm. W, though the changes in slope are small, and that for the $T-W$ scatter is in the opposite direction from that representative of Thorpe Cloud. Fig. 12, in which the allometric growth lines are plotted, shows clearly the difference in the pattern from that of Thorpe Cloud (Fig. 9). It indicates that unless the changes in α had occurred at 25 mm. W, T would have equalled L at 50 mm. (antilog 1.7) with the width at 60 mm. D would of course have equalled L at a smaller value than 50 mm. but this cannot be ascertained from the data, since the scatter is irregular and there are only five specimens $< W=25$ mm. in which $D>T$. A change in the $D-W$ relation would be expected in accordance with the other changes in the value of α. The $D-W$ scatter for all the D_1 Zone specimens measured (where $D>T$) is seen in Fig. 13 to be curved, in which respect it differs from that characteristic of the C_2 Zone.

The changes in α for Narrowdale at 25 mm. W are small, but as they are in opposite directions the total effect is great. T will now never become equal to L or W unless the fossil reaches giganteid dimensions. However, the increase in α for $L-W$ indicates $L=W$ at about 77 mm., which does not exceed greatly the size of the largest specimens.

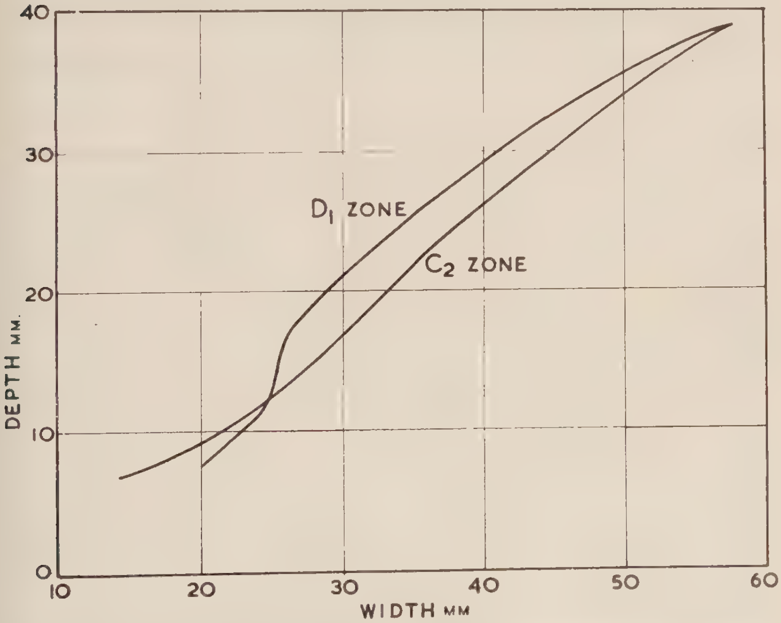

Fig. 15. $D-W$ growth curves for *Pugnax acuminatus*, illustrating the difference in growth rates between the C_2 and D_1 Zone populations

The $L-W$ scatter for all the 346 specimens measured from the D_1 Zone is drawn in Fig. 14, and the reduced major axes A and B fitted. The equations are, for $W<25$ $\text{Log } L=1.233 \log W-0.397$ and for $W>25$ $\text{Log } L=1.064 \log W-0.147$, and therefore the slope α decreases in value at $W=25$ mm. whereas for Narrowdale only it increases slightly as is shown by the broken lines in the graph. These differences are insignificant below $W=25$ mm. However, the break at 25 mm. is more pronounced for the composite sample of 346 specimens than for the Narrowdale sample of 58 specimens; in fact the latter is not typical of the D_1 Zone generally in the size range 25–40 mm. *W*.

In Fig. 14 the reduced major axes C and D are inserted for the combined C_2 Zone sample (from Fig. 11). The growth lines A and C intersect at $W-21$, suggesting that, on average, the small specimens from the D_1 Zone have a lower L/W ratio than those from the C_2 Zone. Beyond $W=25$ the slopes α of the growth lines B and D differ by no more than 5%, but there is a sufficient difference between the intercepts β for the C_2 Zone line D to pass through the D_1 Zone scatter with five-sixths of the points on one side of it and one-sixth on the other. The L/W ratio on average is therefore higher in the D than in the C Zone for the larger specimens, although, as the graph shows, the difference tends to decrease for the old age individuals.

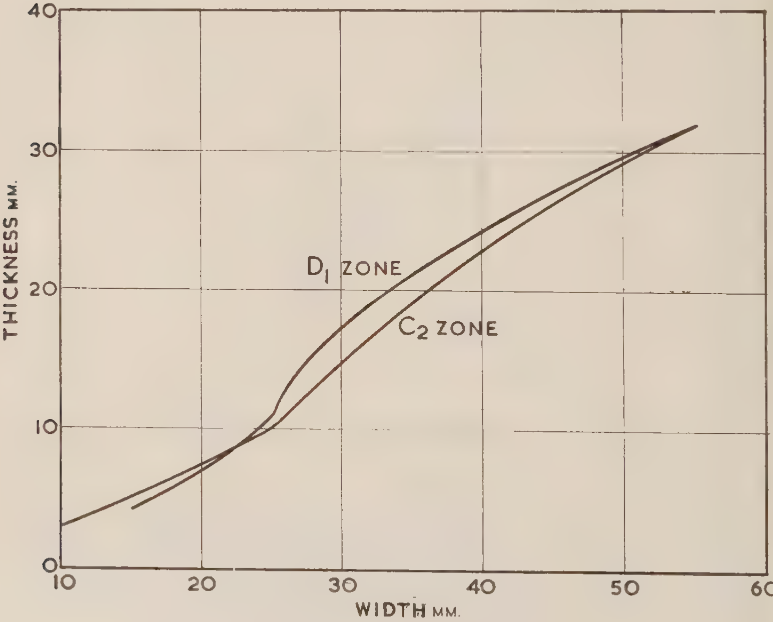

Fig. 16. $T-W$ growth curves; otherwise as in Fig. 15

Because of the curved $D-W$ scatter in the D_1 Zone sample (Fig. 13) a rigorous analysis is not practicable, but a good approximation to the differences between the C and D Zone samples can be made by drawing lines by eye centrally through the scatter diagrams. These lines are reproduced on arithmetical co-ordinates in Fig. 15 and show that in the earlier periods of growth the C Zone specimens tend to be rather deeper than those from the D Zone, but that the curves intersect at about 25 mm. *W*, where there is a rapid increase in the *D*/*W* ratio of the D Zone sample. Then as growth proceeds this ratio gradually diminishes relative to that for the C Zone until in the largest individuals the difference has disappeared. For the *T*−*W* relation the trends are similar but less pronounced (Fig. 16).

Among earlier conclusions (1954, 675) it was stated that the difference in the *T*/*W* relationships were unrelated to stratigraphical levels (e.g. Thorpe Cloud differs from other C Zone collections). However, when the evidence is considered as a whole there does appear to be a phylogenetic trend during the middle growth periods towards thicker and deeper forms.

(e) Schizophoria resupinata (Martin)

Biometric studies have been reported (1954, a) on more than 2000

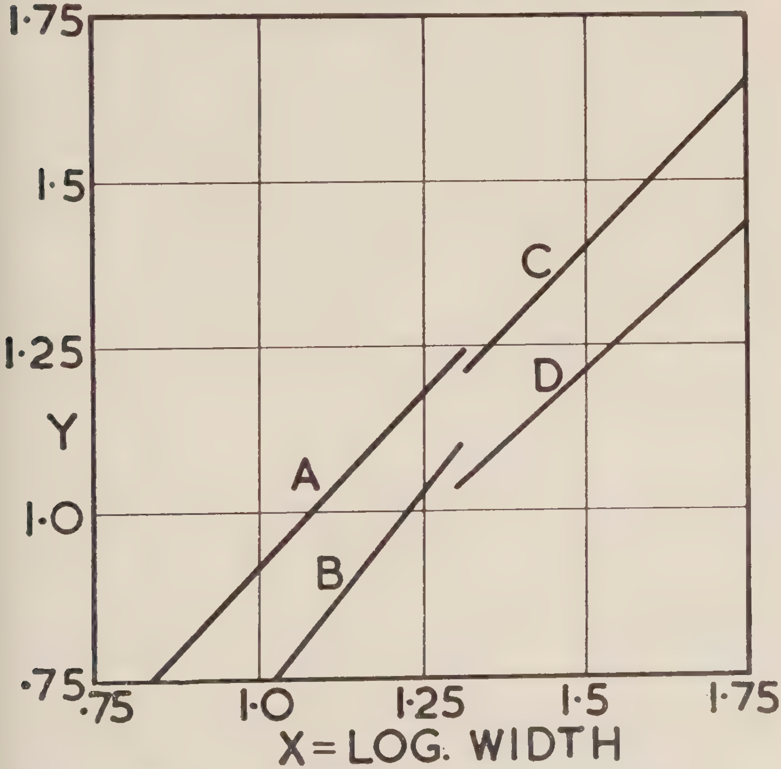

Fig. 17. Growth lines for *Schizophoria resupinata* from the Craven Reef belt. The Y axis represents Logs *L* and *T* and the X axis Log *W*. The equations to the lines A, B, C and D respectively are Log $L = 1.032 \log W - 0.116$, Log $T = 1.225 \log W - 0.498$, log $L = 1.010 \log W - 0.117$ and Log $T = 0.888 \log W - 0.123$

individuals of this species. Growth was shown to be substantially isometric throughout life for the $L-W$ relation. Allometric growth characteristics for $T-W$ indicated a change in α at 20 mm. W for the D_1 Zone, but there was a paucity of specimens less than this size in the C_2 Zone samples.

Since by far the greater number of specimens measured were obtained from the D_1 Zone an attempt has recently been made to supplement the collection from the C_2 Zone, and in particular to secure more small specimens as only 17 individuals had been measured less than 20 mm. in width. The brachiopod bed on the summit of Thorpe Cloud, Derbyshire, has yielded a further 17 measurable specimens, all <20 mm. W. The total number of measured specimens in the C Zone is only 108 compared with some 1970 in the D Zone.

Fig. 17 illustrates the growth features relating L and T to W of the very large composite sample from the Craven Reef of D_1 age. It shows that the

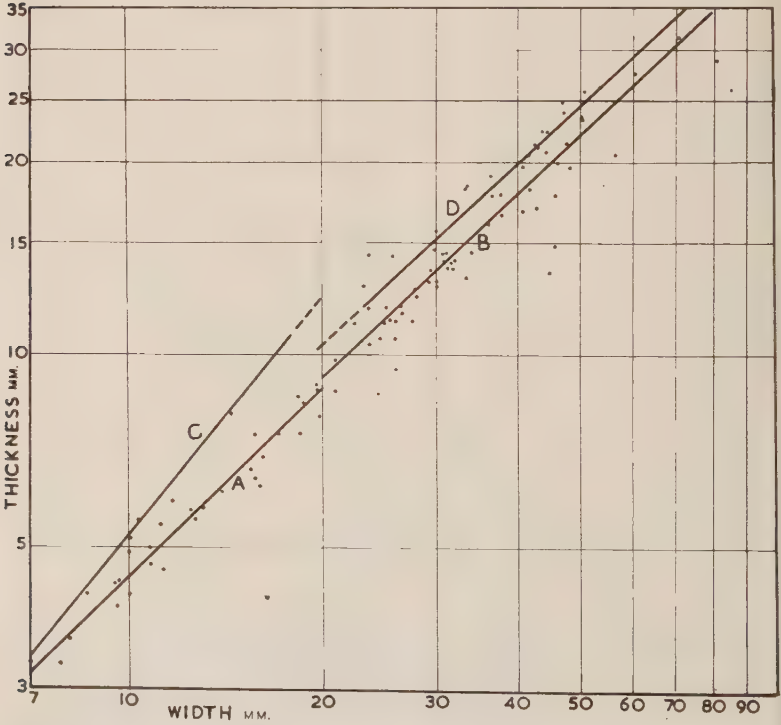

Fig. 18. Scatter diagram of $T-W$ for composite sample of *Schizophoria resupinata* from the C_2 Zone with the reduced major axes A ($T=0.497\ W^{0.978}$) and B ($T=0.555\ W^{0.942}$). Lines C and D represent $T-W$ growth in the D_1 Zone. The equation C (Craven Reef) is $T=0.318\ W^{1.225}$ and for D (all localities) is $T=0.653\ W^{0.927}$

changes in the allometric constants at 20 mm. W (antilog 1.3) have reversed the trend towards equalisation of T and L. But for these changes the average thickness would have been 50 mm. at the length (60) of the largest specimens. Such a high degree of inflation is sometimes seen in small individuals, but never in large ones.

A general conclusion from the earlier work is that the ratios T/W and T/L are significantly less in the C Zone than in the D Zone samples. The more recent observations and analyses have confirmed this view. The 17 measurable specimens recently collected from Thorpe Cloud are all 'thin' forms in keeping with those from other areas at this horizon. Moreover, the many imperfect specimens seen at numerous places support the view that really 'thick' individuals are very rare, if they occur at all, within the limits of the *Caninia* Zone.

The *Dibunophyllum* Zone specimens range from 'thin' to 'thick', these terms being relative, since the T/W and T/L ratios have a unimodal lognormal distribution (1954, fig. 3).

In Fig. 18 the $T-W$ scatter of all specimens measured from the C Zone is shown and the growth lines A and B are fitted from the equations Log $T=0.978 \log W-0.304$ ($W<20$) and Log $T=0.942 \log W-0.256$ ($W>20$). The break at 20 mm. W is not significant. Line C represents the $T-W$ plot of 1630 specimens from the Craven Reef with the equation Log $T=1.225 \log W-0.498$. The slope of this line is almost identical with one representative of 154 individuals from the *Dielasma* bed of Treak Cliff, Derbyshire (also of D age), and is almost outside the extreme limits of the C Zone scatter. Line D (Log $T=0.927 \log W-0.185$) represents all the specimens (192) with $W>20$ mm. from the D Zone. It shows that although the larger D Zone fossils are still, on average, thicker than those from the C Zone the difference is proportionately less than in the size range 10 to 20 mm. W. In the 1954 paper the comment was made that there were no really globose specimens among the large individuals in either zone.

The $L-W$ relation in both the C and D Zones is always isometric, or very nearly so, and there is no significant difference between samples from the two zones, as is indicated by the following equations:

C_2 Zone, composite sample, $W<20$ mm. Log $L=0.978 \log W-0.066$
$W>20$ mm. Log $L=0.961 \log W-0.064$
D_1 Zone, composite sample, $W>20$ mm. Log $L=0.992 \log W-0.092$
*D_1 Zone, Treak Cliff, all sizes, Log $L=1.019 \log W-0.109$
*D_1 Zone, Craven Reef $W<20$ mm. Log $L=1.032 \log W-0.116$
$W>20$ mm. Log $L=1.010 \log W-0.117$

A nearly isometric relation exists also for $T-W$ in the C Zone. The equations for the $L-W$ and $T-W$ lines for $W<20$ differ significantly from each other only in the value of the intercept β. Hence there seems no compelling reason for changes in the value of α during growth, and in fact, unlike the case of the D Zone, no such changes are in evidence.

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* Taken from 1954 paper, 373.

Finally the mechanics of opening and closing the shell may have been a factor causing its thickness to be kept within bounds. It was shown (1954, 376) that the length of the hinge line of the larger individuals is approximately related to the area of the shell. The hinge line length from the smallest to the largest specimens is apparently allometrically related to the width of the shell on the assumption of increases in α at 20 mm. (antilog 1.3) and 50 mm. (antilog 1.7) width (see Fig. 19, which is deduced from a sample of several hundreds of specimens taken at random from the different collections). It can be assumed that if the large specimens had retained a high degree of inflation a prohibitively long hinge line might have been necessitated.

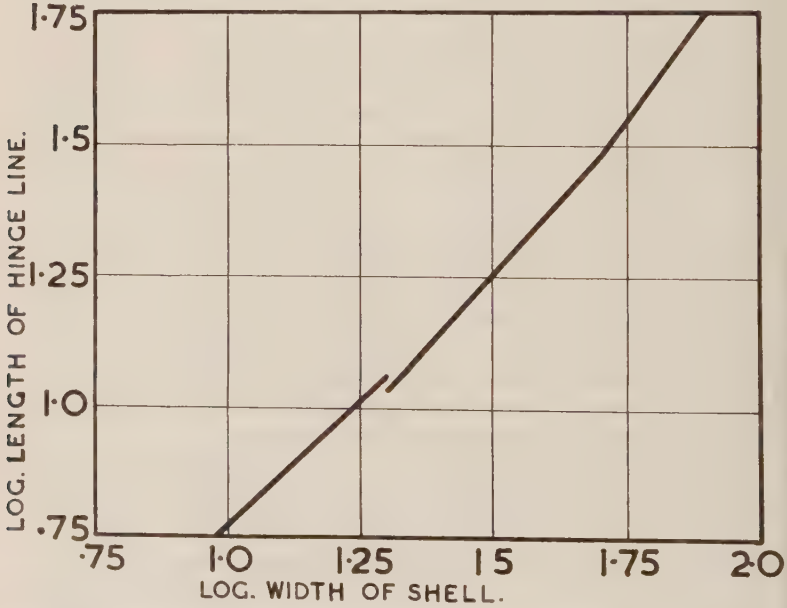

Fig. 19. Allometric growth lines relating length of hinge line of *Schizophoria resupinata* to width of shell; all localities

To sum up it would appear that *Schizophoria resupinata* shows a trend from the C Zone to the D Zone towards thicker forms, but that in old individuals this trend has largely disappeared. In the early stages of growth the allometric coefficient α for $T-W$ is larger in the higher than in the lower zone. At about 20 mm. W the value of α changes from positive to negative in the D Zone samples whereas it remains nearly constant at a little less than unity in the C Zone. The result is that very large shells apparently never assume a high globosity.

(f) Dielasma hastata (J. de C. Sowerby)

We have here an instance of a brachiopod (Parkinson, 1952) in which the relative growth constants changed (at about 19 mm. *W*) without any apparent reason. The break is a very pronounced one which is manifested by a sudden increase in growth of the length and a temporary cessation of growth in the thickness of the shell.

5. ALLOMETRY AS A BIOLOGICAL PRINCIPLE

One of the main objections to the view that allometric growth is to be regarded as a valid biological law is that in order to accord with the facts the growth lines have to be split up into two or more segments. In this paper it has been shown that far from being an argument against such validity, changes in the specific growth constants are in many cases (probably with brachiopods in most cases) an inevitable consequence of allometric growth. Otherwise the late age form of a species will often be so unlike that of the earlier growth stages as to be quite unrecognisable as the same species.

If it be assumed that growth allometry has the status of a biological law its consequences should be seen in the phylogeny as well as the ontogeny of a species. The view is taken here that it is a controlling factor in the evolution of the brachiopoda. Brachiopods evolve slowly, and so far as external form is concerned, the changes in the differential growth parameters appear to act as brakes on potential evolutionary trends. Thus both *Pugnax acuminatus* and *Schizophoria resupinata* (the only two species that have been studied in their relative growth characteristics at two distinct stratigraphical levels) tend to evolve into thicker forms, but the trends are halted and to some extent reversed, following changes in the relative growth rates that result in the late age forms not differing greatly at the two horizons.

In the case of *P. acuminatus* there is (except for the smaller individuals) a slight trend to a higher length–width ratio from the *Caninia* to the *Dibunophyllum* Zone. The difference is most marked when the allometric growth constants change at about 25 mm. width; it tends to decrease towards the late stages of growth.

ACKNOWLEDGMENTS

The author is greatly indebted to Messrs. T. E. H. Gray and H. R. Willcocks, both of the Dunlop Rubber Co. Ltd. Mr. Gray has drawn the fossils and Mr. Willcocks the graphs.

REFERENCES

BOND, G. 1941. Species and Variation in British and Belgian Carboniferous Schizophoriidae. *Proc. Geol. Ass., Lond.*, **52,** 285–303.

HUXLEY, J. S. 1924. Constant Differential Growth-Ratios and their Significance. *Nature, Lond.*, **114,** 895.

IMBRIE, J. 1956. Biometrical Methods in the Study of Invertebrate Fossils. *Bull. Amer. Mus. nat. Hist.*, **108,** 211–52.

KERMACK, K. A. 1954. A Biometrical Study of *Micraster coranguinum* and *M.* (*Isomicraster*) *senonensis. Phil. Trans.*, **237,** 375–428.

——— & J. B. S. HALDANE. 1950. Organic Correlation and Allometry. *Biometrika*, **37,** 30–41.

MUIR-WOOD, H. M. 1951. The Brachiopoda of Martin's *Petrificata derbiensia. Ann. Mag. nat. Hist.* (12), **4,** 97–118.

PARKINSON, D. 1952. Allometric Growth in *Dielasma hastata* from Treak Cliff, Derbyshire. *Geol. Mag.*, **89,** 201–16.

———. 1954. Quantitative Studies of Brachiopods from the Lower Carboniferous Reef Limestones of England. I. *Schizophoria resupinata* (Martin); II. *Pugnax pugnus* (Martin) and *P. pseudopugnus* n. sp.; III. *Pugnax acuminatus* (J. Sowerby) and *P. mesogonus* (Phillips). *J. Paleont.*, **28,** 367–81, 563–74, 668–76.

PRENTICE, J. E. 1956. *Gigantoproductus edelburgensis* (Phillips) and Related Species. *Proc. Yorks. geol.* (*polyt.*) *Soc.*, **30,** 229–58.

SYLVESTER-BRADLEY, P. C. 1958. The Description of Fossil Populations. *J. Paleont.*, **32,** 214–235.

ZUCKERMAN, S. *et al.* 1950. A Discussion on the Measurement of Growth and Form. *Proc. roy. Soc.*, B. **137,** 433–523.

The Geology of North-East Ireland

TO THIS COMPOSITE account of the geology of North-East Ireland, which lies within the region covered by the quarter-inch Sheets 2 and 5 of the Geological Survey of Ireland, contributions have been made by C. H. Emeleus (Mourne granites), A. E. Griffith (Lower Palaeozoics), M. J. Le Bas (Carlingford area), J. Preston (Slieve Gullion area), R. E. H. Reid (Cretaceous), J. A. Robbie (Carboniferous, New Red Sandstone, Lough Neagh Clays), G. P. L. Walker (Tertiary lavas, Interbasaltic, Tertiary minor intrusions (in part)), and H. E. Wilson (Dalradian, Old Red Sandstone, Tertiary minor intrusions (in part)). J. K. Charlesworth has written the remaining sections and co-ordinated the whole.

1. INTRODUCTION

The rocks of this region have a fairly simple distribution (Fig. 1). In the south they consist of the worn-down stumps of the Caledonian orogene of Ordovician and Silurian rocks which are penetrated by the Newry (Caledonian) granite and the Tertiary intrusions of Slieve Gullion, Carlingford and Mournes. Most of the region is occupied by Tertiary flood-basalts which form a saucer-shaped depression, centred about Lough Neagh and the Lower Bann, and break off in escarpments which reveal the underlying Cretaceous, Lias and Trias, the latter flooring the Lagan Valley and its submerged extension, Belfast Lough. The base of the lava-pile rises to more than 1000 feet O.D. in places on the east and west and descends to *c.* —2500 feet O.D. at Langford Lodge, east of Lough Neagh, where the lavas have their maximum known thickness of *c.* 2600 feet (Fowler, 1957; Pugh, 1958, 10).

The flood-basalts lie athwart and largely obscure the two great structural units which strike south-westwards from Scotland. These are the Dalradian rocks of the Highland Border Ridge of north-east Antrim (and their western continuation in the Sperrin Mountains) and the Old Red Sandstone of Cushendun–Cushendall and the Carboniferous rocks of the Ballycastle Coalfield and district west of Lough Neagh. The Highland Boundary Fault runs south of Cushendun and the Sperrins, the Southern Uplands Fault north of the Holywood and Castlereagh Hills.

2. DALRADIAN ROCKS OF CO. ANTRIM

Schistose rocks underlie about seventy square miles between Ballycastle and Cushendun. They are metasediments with considerable thicknesses of epidiorites (metadolerites) and Green Beds which may not be of strictly

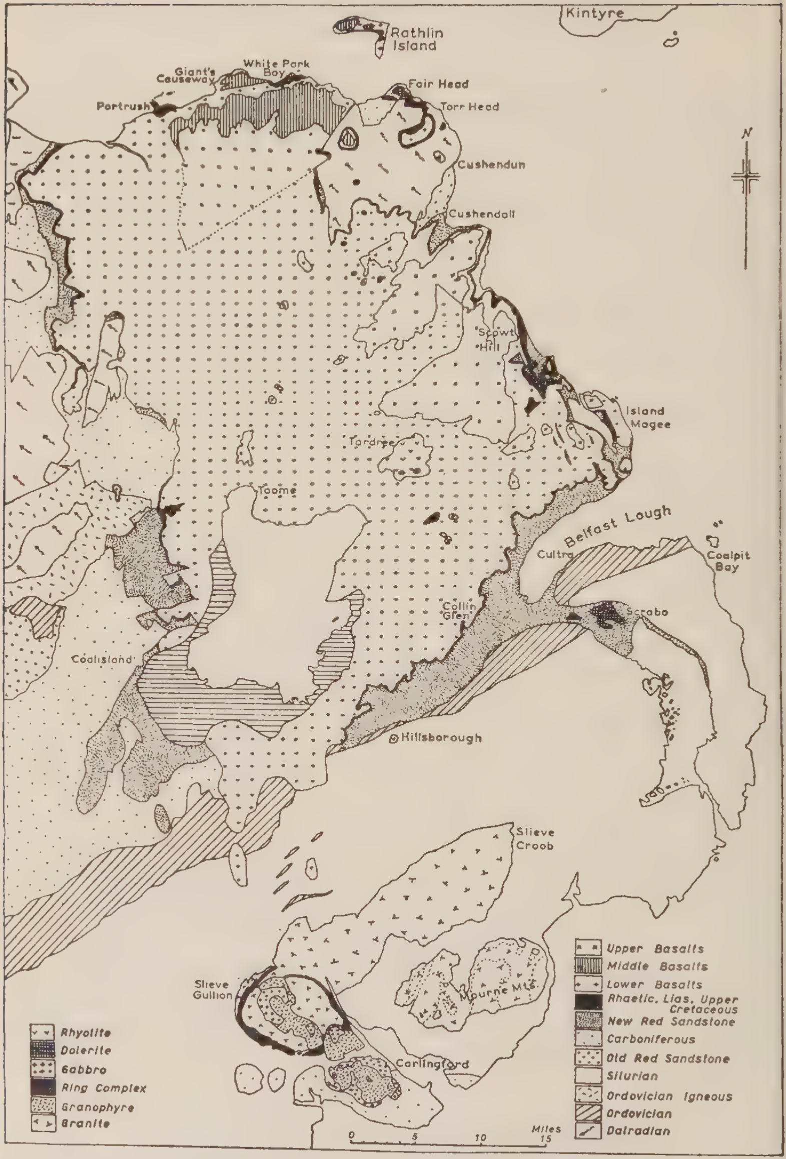

Fig. 1. Geological map of North-East Ireland

sedimentary origin. In the north and west the bedding and foliation of the schists dip at moderate angles to the north-west and minor structures (lineations, corrugations, small overfolds) are either parallel to or normal to the regional dip. South of Torr Head the bedding-foliation flattens out somewhat, and south of Crockan Point the dips swing to the east and the minor structures trend N.–S. with plunge generally to the north.

The structurally highest beds, mainly quartzose mica-schists with some bands of phyllites, flank Knocklayd and cross the country to Murlough Bay. Below them, on the coast south of Ruebane Point and in inland exposures, the beds are more quartzose and include massive grits, sometimes calcareous and often with abundant porphyroblastic albite. Bands of Green Beds and epidiorite occur occasionally.

The Torr Head Limestone, a grey gritty limestone with some bands of coarse black marble, is associated with massive epidiorites which are apparently intrusive and transgressive, and is underlain by very massive felspathic grits and quartz-schists. Epidiorites occur at other horizons and are seen just south of Torr Head in the Altmore Burn which is aligned on a large wrench-fault that may profoundly affect the succession. South of this fault Green Beds lie on several horizons in a predominantly psammitic succession of albite-schists and grits. Chloritic and epidotic types, often with much porphyroblastic albite, are seen at Leckpatrick and Carnaneigh while massive hornblende types appear at Loughaveema and Loughan Bay (Fowler, 1954).

McCallien (1931) correlated the Antrim succession with that of Kintyre, equating the Torr Head Limestone with the Loch Tay Limestone. With Bailey (1934) he suggested that the structure was a recumbent fold gaping to the north-west, probably a continuation of the Carrick Castle fold. This interpretation implies that the Green Beds at Leckpatrick, Loughan Bay and Loughaveema are all of the same group and lie on the inverted limb of the overfold, while the Carnaneigh Green Beds are their equivalent on the upper limb. All the beds north of Leckpatrick are also assumed to be on the inverted limb. The lithology of the Green Beds and the rather scanty evidence from graded and current-bedding do not seem to support this interpretation.

Bailey and McCallien regarded the albite-schists as the recrystallised equivalent of pelites and the characteristic high soda content as an original feature of the sediments. Reynolds (1942) agreed that secondary albite was not due to the Cushendun quartz-orthoclase-porphyry (p. 432) and suggested that it resulted from a complex series of potash and soda migrations from a hypothetical migmatite mass subsequently denuded away. The albites are shown to be older than the quartz-felspar veining associated with the porphyry, the migmatite epoch being contemporaneous with the formation of the 'Older Granites' of Scotland.

3. LOWER PALAEOZOIC

Lower Palaeozoic rocks occupy most of the ground south of the Lagan Valley and Belfast Lough. The Ordovician outcrops in a narrow belt along the northern margin and is brought up in a series of inverted boat-shaped inliers along an axis aligned in the Caledonian direction in Co. Armagh and North Down (see Fig. 1), e.g. Coalpit Bay (Donaghadee), Ballyharry (one mile north of Newtownards), Yates Corner (Saintfield area) (Fowler, 1957), Lessan (near Saintfield) and near Ballynahinch. In the northern strip the rocks consist of grey micaceous grits and siltstones with occasional black chert and mudstones which have yielded Caradocian graptolites (Glenkiln) at Ballygrot, Craigavad and Holywood and Lower Hartfell at Crawfordsburn, Swineley Point and Carnalea. In the inliers the following zones have been recognised: at Yates Corner *Nemagraptus gracilis*; at Lessan and Ballynahinch *Pleurograptus linearis*; at Coalpit Bay, *Dicranograptus clingani* and the Ashgillian *D. complanatus* and *D. anceps*.

The Silurian, which has much the greater outcrop, is composed of greywacke grits, flags, siltstones, occasional coarse quartzose conglomerates and some black graptolitic mudstones. In the north at Coalpit Bay, Conlig and Moneyreagh they belong to the Lower Llandovery (Birkhill).

4. CALEDONIAN IGNEOUS ACTIVITY

The Caledonian orogeny, which compressed the Lower Palaeozoic rocks isoclinally, was accompanied by considerable igneous activity. This is represented by the plutonic Newry complex which was preceded and followed by a hypabyssal phase (see below). Petrographic analogy suggests that the intrusives near Cushendun also belong here, viz. the quartz-porphyry boss of Cushendun, the quartz-felspathic veins and few sills of spessartite, as well as the Cushendall 'felstone porphyry' (see p. 433).

The Newry igneous complex (see Fig. 1) has been fully described by D. L. Reynolds (1934) and in Charlesworth *et al.* (1935). It is intruded for twenty-six miles along the strike of the Silurian greywackes and shales and transgresses the strike at the eastern end where both roof and wall are exposed. The outcrop is restricted in two places, the first NW. of Hilltown, the second west of Newry, due either to the preservation of the roof (Reynolds) or to the existence of contiguous intrusions (Richey). The granite varies considerably in composition and appearance. At its eastern end it includes biotite-peridotite, biotite-pyroxenite, shonkinite monzonite, syenite, augite-biotite-diorite, hypersthene-monzonite and granodiorite (Charlesworth *et al.*, 1935, 452; Reynolds, 1934) while in the big quarries at Goraghwood Station (north of Newry) it is finely granular or porphyritic and biotite-bearing. Usually it is even grained and light grey, though notable amounts of hornblende or biotite, e.g. near Castlewellan, make the rock appear dark and almost basic. In Reynolds' view, the various bands of granodiorite, the strike of foliation of the country rock and the dip and strike of the Silurian inclusions, together with the textural and mineralogical evidence of the granodiorites, suggest a derivation by granitisation of the country rock.

The associated swarm of dykes (Reynolds, 1931), which were intruded parallel to the strike of the Lower Palaeozoic rocks, are best developed in the Ards Peninsula and the adjacent mainland. They fall into two series, first an older and crushed suite, mainly pyroxene-minettes, secondly a younger suite, intruded subsequent to the cessation of stress, which includes dykes characterised by hornblende and others by biotite and pyroxene, both types similar to types found in the Newry complex itself.

5. OLD RED SANDSTONE

A roughly triangular area south-west of Cushendun and Cushendall is underlain by rocks which in the absence of fossils are by analogy with other areas ascribed to the Old Red Sandstone. These sedimentary and pyroclastic rocks rest unconformably on Dalradian schists to the NW. and dip SE. at angles generally between 30° and 40° (Wilson, 1953).

The basal beds are schist-breccia overlain by massive conglomerates, with cracked quartzite boulders and occasional quartz and andesite cobbles in a red sandy matrix, which are well exposed at the Cushendun caves. The succeeding beds, some 3000 feet thick, are mainly coarse red and purple sandstone, with occasional bands of sun-cracked and ripple-marked mudstone. SE. of a strike line running through Cushendall the beds become more conglomeratic with an increasing proportion of andesite boulders until the highest beds, seen on the coast near Salmon Rock, are virtually agglomerates with beds of tuff enclosing large andesite bombs.

Immediately south of Cushendall a triangular area over a mile long is underlain by a mass of porphyritic quartz-andesite or dacite with phenocrysts of quartz, biotite, hornblende and oligoclase/andesine (all but the quartz being much altered) in a partly kaolinised groundmass of felspar microlites. On the north the rock is faulted but on the south seems to be intrusive. An outlying boss forms the hill of Court McMartin in Cushendall; this is possibly the plug of a long-active volcano which supplied part at least of the volcanic detritus in the conglomerates. The main dacite may be a late intrusive event in the centre's history.

For about half a mile south of the dacite coastal sections show massive conglomerates which enclose boulders of an older, probably Old Red Sandstone conglomerate. These conglomerates were long considered to be the base of the Trias which overlies them unconformably near Red Bay Pier. Lithologically and petrographically, however, they closely resemble the Old Red Sandstone and are very different from the soft Triassic sandstones with their wind-rounded grains; they are probably of Upper Old Red Sandstone age (Wilson, 1953).

6. CARBONIFEROUS

The Carboniferous sea, encroaching on the irregular land surface from the south-west, probably invaded NE. Ireland only in Viséan times (George, 1958). Its beds are exposed west of Lough Neagh, in the Belfast area and in the Ballycastle Coalfield. Basal beds, essentially conglomerates of local material, were banked against the lower slopes of the Sperrins in the north-west and the high Lower Palaeozoic country near Armagh. On the north they occur at Kildress (Portlock, 1843; Padget, 1952) and at Derryloran (Fowler & Robbie, 1961) where about 450 feet of the highest beds, probably of C_2S_1 age, are well exposed in the Ballinderry River.

The conglomerates are succeeded by limestones with subordinate sandstones and shales. In SE. Tyrone, the limestones contain several thick sandstones which were formerly quarried for building stone near Cookstown and at several localities NE. of Dungannon. In the Gortnaglush quarry the sandstone rests on shales containing *Pleurodictyum* [*Michelinia*] *megastoma* and probably of S_1 age (Fowler & Robbie, 1961). Limestones of early D_1 age are usually dark grey with thin bands of shale and occasional beds of sandstone. At Sandholes they have yielded *Lithostrotion affine*, *L.* cf. *martini*, *L. portlocki*, *Productus* (*Echinoconchus*) *elegans*, *P.* (*Gigantoproductus*) cf. *kalugensis* and *P.* (*G.*) cf. *maximus* (Fowler & Robbie, 1961). The limestones of the upper part of D_1 and the lower part of D_2 are mostly pure, pale grey or pink and often partly oolitic; they are well exposed in the neighbourhood of Tullaghoge and Loughry Agricultural College and especially in the Killymoon River near the College; the fossils include *Lithostrotion junceum*, *L. martini*, *L. pauciradiale*, *Productus* (*Gigantoproductus*) cf. *maximus* and *P.* (*Krotovia*) cf. *aculeatus*. Three species of *Lithostrotion* are present in 185 feet of D_1 limestone in a borehole at Ballytrea.

Resting on the limestones near Dungannon are the Rossmore Mudstones (Robbie, 1955a) comprising 600 feet of mudstones and shales with thin beds of dark grey limestone near the base; the beds have yielded a comprehensive fauna including *Posidonia* cf. *membranacea*, *Bucanopsis decussatus*, *Glabrocingulum* cf. *armstrongi*, *Straparolus catillus*, *Dimorphoceras* cf. *inflatum*, *Girtyoceras* cf. *coronula*, *Tylonautilus nodiferus* and *Temnocheilus johnstoni*. The lowest beds are characterised by an abundance of small simple corals such as *Cyathaxonia cornu* and *Fasciculophyllum omaliusi* with *Saccamminopsis fusilinaformis* present (usually in a limestone) at about 150 feet from the base—this species has been recorded from Shivey

(McCoy, 1849, 131–2), Killymoon River (Fowler & Robbie, 1961) and Annaghone (Hartley, 1936). The uppermost 100 feet of the Mudstones contain many lamellae and thin ribs of siltstone and fine-grained sandstone. Resting on these striped Measures are about 1800 feet of grits, mudstones and shales, with subordinate fireclays, thin coals and rare limestones—the only important limestone is the Lurgaboy Dolomite, which lies about 150 feet to 200 feet above the base—which comprise the Millstone Grit. Most of our information regarding this formation, which outcrops between Dungannon and Coalisland, has been obtained from bores (Fowler & Robbie, 1960; Robbie, 1955a). Fossils are numerous on certain horizons and include *Chonetes* cf. *hardrensis*, *Productus* cf. *carbonarius*, *Edmondia laminata*, *Nuculana attenuata*, *Nuculopsis gibbosa*, *Palaeoneilo laevirostris*, *Bucanopsis* cf. *undatus*, *Angyomphalus* (*Trepospira*) cf. *junior*, *Glabrocingulum* cf. *armstrongi* and *Straparolus catillus*. The only diagnostic fossil is an early mutation of *Tylonautilus nodiferus* believed to be of E_1 age (Robbie, 1955a) which is present in shales above the Lurgaboy Dolomite. Another form of *T. nodiferus* indicative of E_2 age occurred about 350 feet higher in the sequence (Robbie, 1955a). Zones H and R are probably absent from the area. The Main or Drumglass Coal near the bottom of the succession (Robbie, 1955a) and the Yard Coal towards the top (Fowler & Robbie, 1961) are the only important coals in the Namurian; both are virtually worked out.

The base of the Coal Measures, the Coalisland Marine Band (Fowler & Robbie, 1961), is exposed in the Coalisland Brickpit: it is now known to overlie Hardman's Wee Coal (Hardman, 1877) and contains the diagnostic *Gastrioceras subcrenatum*. The Coal Measures (Ammanian) comprise about 600 feet of mudstones and shales with some siltstones and sandstones, some thick beds of fireclay and eight workable coals—these include the Annagher Coal, the thickest local Ammanian seam—having a total thickness of about thirty-two feet. The rocks of the exposed coalfield are disposed in a pitching synclinal basin around Coalisland; all the seams are practically worked out.

In the very small faulted trough of the Annaghlone Coalfield the four highest coals of the Coalisland succession have been proved. Only one, the Annagher Coal, was of workable thickness.

Carboniferous rocks are exposed near Belfast at Cultra and Castle Espie. At Cultra (Lamplugh *et al.*, 1904) a small area of conglomerates, calcareous sandstones and grits and dark grey or black fossiliferous shales have abundant *Modiola macadami* and other fossils including *Lithostrotion junceum* and *Machrocheilus acutus*, probably of D_2 age. Little can now be seen of the red or salmon-coloured, finely crystalline limestone in the waterlogged quarries at Castle Espie, two miles ESE. of Comber (Lamplugh *et al.*, 1904). The outcrop is very small.

At Ballycastle the Carboniferous rocks occupy some eight square miles between Ballycastle and Murlough Bay. They belong to both Lower and Upper Carboniferous, the boundary between them being somewhere between the Main Limestone and the Main Coal.

The basal beds comprise over 500 feet of soft pebbly sandstones and conglomerates consisting of small pebbles and sand from the adjacent metamorphic rocks. They are overlain by about 120 feet of decomposed lavas, which are exposed in the Carey River, at Murlough Bay, and at Bath Lodge, and have been compared with Markle and Jedburgh type lavas in the Calciferous Sandstone Series of Scotland (Wright, 1924a). Resting on the lavas are nearly 200 feet of tuffs and sandstones, followed by the lowest group of shales with several coal seams and fireclays, in all about 150 feet of measures. Just over half-way up the succeeding sequence of more than 550 feet of sandstones with some thin shales and mudstones is the Carrickmore Blackband Ironstone overlain by about forty feet of shales carrying marine fossils and containing a thin limestone.

Resting on these predominantly arenaceous beds are about seventy feet of fossiliferous shales with calcareous ribs and one thick bed, the Main Limestone, which is exposed on the foreshore near the North Star Dyke and is probably equivalent to the Hurlet Limestone of Scotland. Among the abundant fauna is *Productus* (*Gigantoproductus*) *latissimus s.s.*, which is restricted to the P_2 zone. Approximately 110 feet above the Main Limestone is the Main Coal which has been worked out over most of the area. About 120 feet of sandstone separate the Main Coal from McGildowney's Marine Band which consists of two bands of fossiliferous shales separated by twenty feet of sandstone. The fossils in the marine horizon include *Schellwienella rotundata*, which is regarded as belonging to the Upper Limestone Group of Scotland and indicative of E_1 (Lower Namurian). The remaining measures (about 150 feet) are mainly sandstones with some shales and a few coals, one of which, the Hawk's Nest Coal, has been worked over much of its outcrop.

7. NEW RED SANDSTONE

Permian strata outcrop in two small areas only, one at Cultra on the southern shore of Belfast Lough and the other at Tullyconnell near Grange, SE. of Cookstown. At both localities the beds rest on Lower Carboniferous rocks. At Cultra, the outcrop, accessible only at low tide, extends for about one quarter mile along the foreshore. Its red sandy marls rest with a breccia on Lower Carboniferous shales and are overlain by pale, buff-coloured magnesian limestone. Among the fossils recorded by W. King (1853) were '*Productus horridus*, *Bakevellia antiqua*, *Pleurophorus costatus*, *Schizodus schlotheimi*, *Arca* cf. *tumida* and *Turbo helicinus*'.

The exposure at Tullyconnell (King, 1857) is now almost completely overgrown; a few blocks and pieces of soft yellow or creamy, porous, fossiliferous dolomitic limestone are alone to be seen. However, a few feet of relatively unfossiliferous pale yellow, thickly bedded dolomite are visible on the east bank of the Killymoon River about one quarter mile north of Tullywiggan Bridge.

A few boreholes east of Grange (Fowler, 1955) have recently established a threefold division of the Permian in this district. The Basal Sands, dull red or brownish-red sandrocks or sandstones vary in thickness from a few inches to twenty-five feet. Resting on these is the highly fossiliferous Magnesian Limestone, a yellowish dolomite, usually about seventy feet thick, which varies in texture but is usually oolitic and often contains cavities lined with calcite crystals. The fauna includes *Batostomella columnaris*, *Thamniscus dubius*, *Bakevellia antiqua*, *Pleurophorus costatus*, *Schizodus schlotheimi*, '*Natica*' *leibnitziana* and *Omphalotrochus helicinus* (Fowler, 1955). The Magnesian Limestone is usually overlain by the Upper Permian Marl, a group of marls associated with beds of gypsum. In places carbonate has been deposited instead of sulphate.

Despite the recent borehole information the exact age of the Magnesian Limestone is still in some doubt. King referred the Grange dolomite to the Upper Magnesian Limestone and J. W. Kirkby (1861) correlated the Permian of Grange and Cultra with the Lower Limestone of South Yorkshire. The evidence seems to favour King's interpretation (Fowler, 1955) though the presence of *Productus horridus* at Cultra suggests a Lower Magnesian Limestone age for at least part of that succession.

Breccia, consisting of blocks of Carboniferous Limestone, grit and sandstone embedded in a reddish sandy matrix and resting on Carboniferous Limestone, is exposed in the old 'marble' quarries on the west side of Armagh. The breccia was considered to be of Permian age (Hull, 1873) but more probably forms the basal beds of the Trias.

Triassic rocks appear at many localities from beneath the scarp of the Antrim Plateau. The most important outcrops are at Larne, about Red Bay and at Murlough Bay on the east, from north of Cookstown to near Armagh on the west, and on the south along the Lagan Valley to the sea to beyond Belfast with an easterly extension into the upper reaches of Strangford Lough. The rocks are divisible into a Bunter and a Keuper Series. Where the Bunter Series does not rest on Permian, for example, at Murlough Bay, near Cookstown, Dungannon and Armagh, at Newtownards and in the Lagan Valley south-west of Lisburn, the basal beds are conglomerates, up to several hundred feet thick in places, containing pebbles derived from local rocks. Thus at Murlough Bay the pebbles are of schist and vein quartz whilst those near Cushendall are of Cushendall porphyry and boulders of quartzite from the Old Red Sandstone. Except at

Murlough Bay and a few other places, the basal conglomerates are succeeded by 200 to 300 feet of silty, sun-cracked marls with many wisps, lenses and irregular thin bands of sandstone, the whole named the Bunter Marls (Fowler & Robbie, 1961). Where Trias rests on Permian these Marls are continuous with the Upper Permian Marl but are distinguished from this by their typical silty nature, their characteristic sedimentary structures and the absence of beds of gypsum. Evidence from several deep borings in Belfast (Lamplugh *et al.*, 1904) suggests that the Lower Marls of Hartley (1943) include the Upper Permian Marls.

The Bunter Marls pass gradually upwards into the typical red Bunter Sandstone which averages 1000 feet in thickness. About 120 feet of well-bedded sandstone is exposed in the old freestone quarries at Scrabo where many thin reddish clay-partings and ripple-marks, sun-cracks and rain pits are displayed.

In several boreholes drilled in recent years (Fowler & Robbie, 1961) to the east of Grange, it has been possible to distinguish from the Bunter Sandstone about forty feet of yellow and brown sandstone which it is believed represents the Keuper Sandstone. Similar rocks are exposed in Belfast at Whiterock Road, at the lower entrance to Fortwilliam Park and in the old sea-cliff on the Shore Road.

Resting on the Keuper Sandstone are 1000 feet of red and grey-green marls of the Keuper Marls with veins of fibrous gypsum and beds of salt at certain horizons; the green marls are exposed in Collin Glen and at Waterloo near Larne. The Keuper Marl was at one time extensively dug for bricks on the outskirts of Belfast. These brickpits showing gypsiferous marls are now abandoned and are gradually being filled, although one is still working near Collin Glen.

8. RHAETIC AND LIAS

The Rhaetic and Lias emerge from beneath the Cretaceous around the edge of the plateau-basalts where they give rise to landslips. Thus they appear near Garron Point and in a few places about Belfast, including Collin Glen, west of which both Rhaetic and Lias are absent. Lias is also found at Whitehead, Barney's Point (Island Magee), Waterloo (one mile north of Larne), east side of White Park Bay and at Portrush. The shales are very fossiliferous and revised lists of fossils have recently been published (Charlesworth & Preston, 1960). The beds belong only to the Lower Lias (Hettangian, Sinemurian), the zones of *planorbis* and *angulata* occurring at all localities, with the addition of *bucklandi* at Waterloo, of the zones up to *obtusum* at Collin Glen and *bucklandi*, *semicostatum*, and higher horizons up to and including *raricostatum* at White Park Bay where the Irish Lias in surface exposures is most fully developed. The very lowest or Pre-*planorbis* beds, with *Ostrea liassica* and *Modiolus minimus*, are found in Collin Glen and other places. Lias beds, 410 feet thick, have been proved in the Mire House Bore, Dungannon; they belong to the *planorbis* and *angulata* Zones (Anderson, 1954).

Remanié fossils of Middle and Upper Lias age have been obtained from the basal Cretaceous conglomerate at Murlough Bay (Hartley, 1933; Versey, 1958) and at the north-east corner of White Park Bay. No remanié fossils from the Oolites have been seen though beds of this age probably at one time covered the region.

9. CRETACEOUS

Cretaceous beds are exposed in a narrow strip around the edge of the plateau-basalts, in Rathlin Island and at Templepatrick and a few other inliers. They belong to the Upper Cretaceous only and except in the highest zone (*mucronata*) are marginal in character, being glauconitic greensands in the main and comparable with the English Aptian and Albian. The Chalk or White Limestone is largely restricted to the *mucronata* Zone but extends downwards to the *Uintacrinus westfalicus* Zone.

Deposition began with the Cenomanian transgression but all deposits up to lowest Turonian are of greensand facies. These Hibernian Greensands (Tate, 1865) are only seen in south-east Antrim, viz. from Lisburn to Belfast and Glenarm. They are usually thirty to sixty feet thick and divisible lithologically into (a) Glauconitic Sand, a dark green glauconitic sand with a grey calcareous matrix, (b) Yellow Sandstone, a sparsely glauconitic yellow to grey sandstone (sometimes cherty), silts and marls, and (c) Glauconitic Sandstone, quartz-glauconitic sands and sandstone—this consists of two horizons (Reid, 1958), namely, Cenomanian, seen at Collin Glen, and late Turonian–early Senonian, e.g. at Larne and Island Magee, which are identical lithologically and only distinguishable by their fossils; a regression during lower and middle Turonian times was responsible for the interruption.

The two lower divisions contain fossils of which some are typical of the Albian Upper Greensand of England, e.g. *Exogyra conica*, *Pecten* (*Aequipecten*) *asper*; these are facies fossils. The true age is shown by species of *Schloenbachia*, *Acanthoceras* and *Mantelliceras* and other forms, e.g. *Actinocamax primus* (Hancock, 1960).

The lower of the two divisions of the Glauconitic Greensand (see above), the Lower Glauconitic Sandstone, is specially characterised in parts by its abundant *Exogyra columba*, the upper division by bands of fragments of a large *Inoceramus* (hence Hume's (1897) *E. columba* and *Inoceramus* Zones). This upper division is shown to be post-Cenomanian by species of *Gibbithyris* and *Cretirhynchia* which in England are found in the Zones

Holaster planus-Micraster coranguinum (Hancock, 1960; McGugan, 1957); it also yields fossils such as *Spondylus spinosus*.

The characteristic Senonian deposit of the Zones of *Micraster coranguinum* and *Gonioteuthis quadrata* is the Glauconitic Chalk, a diachronous deposit, and at White Park Bay and Garron Point has a local development of White Limestone. In the south-east, the Glauconitic Chalk is transitional between the Upper Glauconitic Sandstone and the succeeding Chalk but in the north it is transgressive on older rocks and is basal in facies. The outcrop continues from south-east Antrim around the east and north coasts into Co. Londonderry, except for some local interruptions between Ballycastle and Cushendall where it crosses the Highland Border Region, has a conglomeratic base and perhaps submerged the area only in *Belemnitella mucronata* times; the thickness of the conglomeritic facies is two to five feet in the south-east, nought to two feet between Cushendall and Ballycastle and fifteen feet in Co. Londonderry (Tircreven Burn).

A special feature of the Glauconitic Chalk is its frequent richness in remains of Hexactinellid sponges which are absent from lower deposits (Reid, 1958). A conspicuous sponge bed is developed in the coastal outcrops between Glenarm and Island Magee.

The Glauconitic Chalk shows sand and glauconite grains in a matrix of white or creamy chalk and is usually moderately hard; the grains are sometimes concentrated along irregular seams. A 'nodular' facies in the Belfast area, the so-called Mulatto, has sedimentary features analogous with those of the English Chalk Rock. The pebble contents of the conglomeratic facies vary with the underlying rocks; at Murlough Bay–Torr Head, for instance, they are chiefly Dalradian with predominant quartz and with Triassic fragments as minor elements. At White Park Bay, a conglomeratic basement is rich in small phosphatised pebbles or 'coprolites'.

The age of the Glauconitic Chalk below the *B. mucronata* Zone is variable. The Belfast Mulatto contains *G. quadrata* and *Offaster pilula* occurs at the top of softer material below. Between Belfast and Murlough Bay, the *G. quadrata* Zone is usually unrepresented, its place being marked by a discontinuity and a strong bedding plane. The Sponge Bed of Island Magee is thought to be of *Marsupites* age (Hancock, 1960; Anderson, 1957; Hume, 1897), though in parts it may be slightly later (Hancock, 1960; Reid, 1958). The Torr Head–Murlough Bay conglomerate is not older than Turonian and contains a sponge suggesting middle Senonian age (Reid, 1959). The Glauconitic Chalk at White Park Bay is apparently restricted to the *M. coranguinum* Zone but at Tircreven Burn, Co. Londonderry, extends from this zone to the base of the *B. mucronata* Zone.

The White Limestone, the most important member of the Irish Cretaceous, is typically a very hard white chalk with numerous stylolytic partings. Abundant flint nodules are arranged in successive bands and the distinctive 'paramoudras' are seen in places, e.g. at Moira. The zonally low chalk, that of *Uintacrinus–Marsupites* age, has a gritty texture, is more greyish or creamy in colour, and has irregular marly partings in place of the stylolites. The lowest part is typically flintless.

The main mass of the White Limestone is of *B. mucronata* age. The chalk of this zone is present in all outcrops; it is transgressive outside the area of the earlier Cretaceous deposits and then usually shows a thin conglomeratic and/or glauconitic basement bed. It is much thicker than the rest of the formation, reaching over 200 feet and exceptionally in bores in the Coalisland area to 480 feet (Hartley, 1948). The zonally low chalk of White Park Bay is marked as such by the occurrence of *G. quadrata* and *Marsupites* and by *Uintacrinus* in its lower part (Hancock, 1960). *O. pilula* is not recorded, but this does not seem to be due to a break in the succession.

A re-worked Pellet Chalk at Ballycastle has yielded Maestrichtian foraminifera (McGugan, 1957) though no chalk of this age is known *in situ*.

The Irish Cretaceous therefore records a Cenomanian transgression followed by a Turonian regression through the zones of *Inoceramus labiatus–Terebratulina lata*, and this in turn by a progressive transgression through the late Turonian and Senonian, with principal advances in the late Turonian, the period of the *M. coranguinum* Zone and early *B. mucronata* Zone, the last apparently preceded by regression in the east.

10. TERTIARY IGNEOUS ACTIVITY

Flood-basalts. Basic lavas underlie some 1500 square miles (see Fig. 1), the largest British remnant of the extensive North Atlantic flood-basalts. They rest in most places upon a thin residual and often lateritic bed of clay-with-flints, locally containing plant remains, which in turn overlies an eroded surface of Chalk. The lava-pile, which is magnificently exposed in the escarpment cliffs, is made up of individual flows which are commonly inclined at 5–10° and average about twenty feet in thickness. Thin pahoehoe flow-units are, however, only a few feet thick while other lava flows are 100 to 150 feet thick.

The lavas were erupted sub-aerially: they frequently have lateritic weathered tops, are occasionally associated with lignite and the remains of terrestrial plants and have neither pillow-lavas nor intercalated marine sediments. Trap featuring is uncommon but is seen west of Carnlough, on the southern side of Glenariff and in Rathlin Island.

The basalts are divisible into three series (see Fig. 1). Those of the Lower and Upper Series are olivine-basalts: olivine is often visible in hand specimen but is frequently brown or red due to alteration. The average content of olivine is 15–20% but rises to 30–50% in the occasional picrite-basalts (Patterson, 1955a, 161; Walker, 1959, 192). The thinner flows are usually badly altered, having suffered from zeolitisation and both Tertiary and present-day weathering. The Middle Series of North Antrim are tholeiites (Patterson, 1955; Tomkeieff, 1940), distinguished microscopically by the very fine grain-size, the virtual absence of olivine, and the presence of glass. The flows have a two-tiered columnar jointing, surmounted by a slaggy top.

Gravity differentiation, which took place before or during eruption (Tomkeieff, 1940), is sometimes revealed in a basalt flow, e.g. in Island Magee (Tomkeieff, 1934), by a downward increase in olivine content, or in a composite flow in which olivine-rich and relatively olivine-poor components are separated by sharp contacts. Rare types include an occasional basalt lava bearing sparse phenocrysts of plagioclase up to three inches long, basalts rich in microphenocrysts of plagioclase, e.g. on Agnew's Hill, and mugearite and quartz-trachyte (Patterson, 1951; Walker, 1960).

The amygdales in the basalt lavas are characteristically occupied by secondary minerals, including calcite, aragonite, quartz, chalcedony, opal, apophyllite, celadonite, various saponite-like minerals and zeolites; the latter, in order of frequency, are chabazite, thomsonite, analcite, levynite, natrolite, mesolite, stilbite, gmelinite, heulandite, phillipsite, scolecite, gismondite, laumontite and mordenite. The Antrim lavas furnish the best British localities for phillipsite (Giant's Causeway area), gmelinite (Island Magee, Glenarm) and apophyllite (Belfast district), and the only known British localities for gismondite. The amygdale minerals have a distribution which can be mapped (Walker, 1951). Distinctive assemblages of minerals occupy flat-lying but discordant zones in the lavas, the relationships of the zones indicating that zeolitisation was very late in the volcanic history.

Interbasaltic horizons. The Lower, Middle and Upper Basalts are separated from one another by very prominent laterite horizons. In north Antrim two such interbasaltic beds are known (Patterson, 1955); elsewhere there is only one horizon which divides the lavas into a Lower and an Upper Series (Cole *et al.*, 1912). These lateritic horizons, whose chemistry and mineralogy Eyles has fully discussed (Eyles, 1952), represent pauses of unusually long duration in the outpouring of the basic lavas, for the alteration extends downwards into the basalts to a depth of several tens of feet.

The laterite is associated in a few places with detrital beds, e.g. detrital bauxite at Craigahulliar, SE. of Portrush, and in east Antrim has much rhyolitic material, including quartz grains and rhyolite fragments (Cole *et al.*, 1912; Reynolds, 1951). Discontinuous beds of lignite, e.g. in Craigahulliar (Charlesworth, 1953, 144), have been recorded from several places, and leaf impressions from Ballypalidy.

Acid volcanic rocks. Rhyolite and pitchstone outcrop over some twelve square miles at Tardree and Sandy Braes in mid-Antrim (Charlesworth &

Preston, 1960, fig. 10); the rhyolite is rich in phenocrysts of felspar and quartz. Plug-like intrusions of rhyolite occur at Templepatrick—this was bored into to a depth of 1300 feet (Fowler, 1956)—and near Hillsborough, Co. Down.

Plugs. About thirty dolerite plugs are known to penetrate the lava plateau and the sedimentary rocks around its periphery (see Fig. 2). The plugs range in diameter from a few score yards to about one mile. Most are vertical or nearly vertical and in plan vary from circular to extremely elongate, the elongation being normally parallel to the regional dyke swarms. The most spectacular is Slemish (1437 feet) which rises steeply as

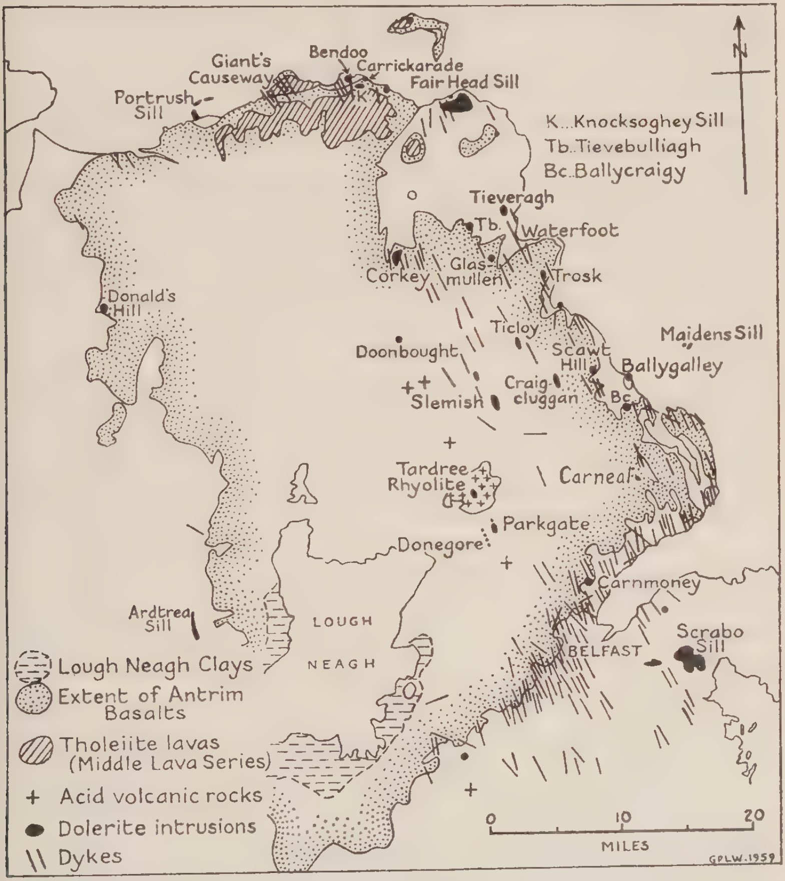

Fig. 2. Map of the Tertiary minor intrusions of North-East Ireland (drawn by G. P. L. Walker from published sources)

an elongated dome above the surrounding basalt upland; other notable topographica lfeatures are Carnmoney Hill, Belfast, Ballygalley Head, Scawt Hill, Tievebulliagh and Tieveragh near Cushendall, Bendoo at Ballintoy Harbour and the Brockley plugs on Rathlin Island.

Most of the plugs are ophitic olivine-dolerite, sometimes with an olivine-rich margin, e.g. Tieveragh and Tievebulliagh (Tomkeieff, 1940a) and Corkey (Walker, 1959). Trosk is unique in being composed entirely of picrite-dolerite with 45% of olivine (Walker, 1959). Carnmoney and Glasmullen are olivine-free (Patterson & Swaine, 1957).

The degree of thermal metamorphism of the country rock varies considerably. Intrusive contacts are rarely clear; the Tieveragh plug has altered the Old Red Sandstone to buchite (Tomkeieff, 1940a) and the Chalk is intensely metamorphosed at Scawt Hill (Tilley & Harwood, 1931), Ballycraigy (McConnell, 1955) and Carneal, though in contrast it is practically unaltered at Bendoo (Tomkeieff & Patterson, 1953) and Ballygalley Head. Tievebulliagh (Agrell & Langley, 1958), an inclined plug, has markedly affected the adjacent Lower Basalts and has converted the Interbasaltic Bed, relict blocks of which are seen as xenoliths, into a tough, heavy corundum-mullite-haematite-hornfels. A laterite/lithomarge horizon is similarly intensely altered at Brockley (Dawson, 1951). Neolithic man used both these porcellanites for making stone axes (Jope, 1953). In no case is continuity between intrusion and adjacent lava flow observed.

Vents. Major agglomerate-filled vents, with associated beds of tuff low down in the Lower Basalt succession, occur at Carrick-a-raide (Tomkeieff & Patterson, 1948), Kenbane (Fowler, 1954) and Ballygalley Head (Walker, 1959): the ash beds derived from Carrick-a-raide and Kenbane, which were probably concurrent, can be traced for over three miles in cliff sections. The vents are associated with intrusions which succeeded the explosive phase of the activity. Smaller agglomerate or tuff pipes or gas volcanoes occur in the lavas and Chalk on the North Antrim coast (Dawson, 1951; Fowler, 1958; Patterson, 1955). Though some of the phenomena are collapse features in the Chalk there are at least twenty such pipes in North Antrim; the agglomerates are predominantly of the country rock (basalt, Chalk), with only rare and small quantities of earlier material. Many are clearly gas-volcanoes of the Schwabian type (Cloos, 1941).

Sills. Several thick but laterally restricted sills of olivine-dolerite have been intruded into the sub-basalt sedimentary rocks and two are known which occur in the lava series, viz. Corkey (Walker, 1959) and Knocksoghey (Tomkeieff & Patterson, 1947), the latter 125 feet thick. One of the best exposed sills forms the top of Fair Head (636 feet). This is 270 feet thick at maximum and thins to the SE., transgressing up through Carboniferous, Triassic and Cretaceous strata, and to the west where it interdigitates with

Carboniferous shales. To the south it dips more or less with the Carboniferous rocks. Its upper part has extensive late-stage veins and sheets of dolerite-pegmatite and veins of magnetite-rich, fine-grained basalt, and is penetrated by a few thin irregular basalt dykes. In one area it has large xenolithic rafts of Carboniferous sandstone. A complex of minor sills is associated to the south and west at higher stratigraphical horizons, and one or more subparallel sills at a lower level outcrop along the talus below the headland.

The Portrush Sill, over 100 feet thick—the base is not exposed—forms the promontory of Ramore Head and the arcuate chain of islands known as the Skerries. It is notable for a remarkable series of late-stage veins including mobilised hornfels and pyroxene-plagioclase veins of several types, of syntectic origin (Harris, 1936), and for the extensive baking of the Lias shales: this 'Portrush Rock', a hard, fine-grained porcellanite with recognisable fossils, particularly ammonites, was the subject of controversy between 'Neptunists' and 'Vulcanists' in the late eighteenth century (Portlock, 1843).

Scrabo Hill, Newtownards, is capped by an extensive sill and has thin sills in the underlying Triassic sandstone. A bore just off the outcrop of the main intrusion penetrated 510 feet of dolerite. Other sills occur in the Maidens (Charlesworth, 1937a), at Ardtrea, Co. Tyrone (Patterson, 1944), and at Knocksoghey. Corkey is the only known intrusion into the lavas well up in the succession.

Dykes and fault intrusions. The numerous Tertiary dykes of NE. Ireland trend generally NW. and group themselves into swarms with plutonic foci—Mournes (Tomkeieff & Marshall, 1935), Carlingford, Slieve Gullion, Tardree and Hillsborough (Charlesworth & Hartley, 1935; Tomkeieff & Marshall, 1940). The relatively few dykes which cross the general trend may be earlier (Walker, 1959). Two dykes have been found feeding lava-flows (Patterson, 1950; Walker, 1959, 196).

Virtually all the Antrim dykes are olivine-basalt or dolerite, sometimes with zeolites in both marginal amygdales and groundmass. The Mourne swarm, however, has a uniquely large variety of types ranging from olivine-dolerite to acid porphyry and felsite. Horizontal or prismatic jointing and vertical platy jointing are both common. In the harder rocks—basalt lavas, sandstones, greywackes—the dykes are generally straight and regular but tend to be exceedingly irregular in form and direction in Triassic marls, e.g. on the foreshore at Carrickfergus, and in the Interbasaltic Beds, e.g. at Giant's Causeway (Roveran Valley Head).

While the thermal metamorphism of the country rocks is usually slight, a few of the larger dykes have a wide contact zone, as at Waterfoot (Reynolds, 1940), Portmuck (Walker, 1948) and Carrickfergus Castle—this may be an elongate plug. Kaolinisation and chloritisation have reduced some of the basalt dykes in the Triassic rocks to 'white trap' (Charlesworth & Cleland, 1928). The 'Carrickmore Dyke', three miles east of Ballycastle, an inclined sheet intruded along a fault plane, has converted the adjacent Carboniferous shales to porcellanite for a distance of twelve feet. Apophyses form three small plugs which enclose much xenolithic porcellanite and stand out as islands. The small elongate plug at Ballyconaghan, Rathlin Island, is another fault intrusion.

Plutonic Rocks. Plutonic centres of Tertiary age occur in the Mournes and in the Slieve Gullion and Carlingford areas. The Mourne granites (Fig. 3) form the high ground in south Down between Newcastle and Rostrevor, intrude Silurian sediments and truncate a suite of dykes and minor intrusions, mainly of Tertiary age. J. E. Richey (1927) distinguished two major centres—an eastern one with three distinct granites and a western one, now known to contain two granites (Emeleus, 1955). A cone-sheet system is associated with the granites (Tomkeieff & Marshall, 1935). Particularly convincing intergranite contacts are exposed in the upper Glen River Valley where G1 roofs G2, on the summit ridge of Slieve Bingian with G2 as roof and wall to G3, and north of Slieve Bernagh (on Slievemeel More) and near the Diamond Rocks where G1 roofs G2. In a tunnel under Slieve Bingian (Robbie, 1955) the junction between G3 and G2 is sharp and dips east at 50°; nearby G2 is cut by sheets of G3; the granites are altered along NNE.–SSW. zones with the formation of kaolinite—alteration of G2 with kaolinisation had previously been recorded from SE. of Slieve Corragh, WSW. of Slieve Commedagh (White & Patterson, 1949); and a late-stage mineralisation vein contained small amounts of fluorite, sphalerite, covelline and galena (one of the few examples of Tertiary lead in the British Isles). Replacement veins may be examined in the quarry at the west end of the Silent Valley dam (G3) and in disused quarries (G2) SE. of Newcastle Harbour at about 700 feet (Nockolds & Richey, 1939).

In the western centre, the Pink or Outer Granite (G4) encloses a later intrusion, the Inner Granite (G5). This granite is medium to fine grained and non-porphyritic. Mineralogically it differs but little from G4; it has a small amount of green amphibole. The conspicuous but small drusy cavities contain occasional segregations of magnetite with mica: small crystals of tourmaline have been found. The marginal G5 in old quarries east of Eagle Mountain has a well-developed mariolitic facies.

At the contact with G4, G5 is relatively fine-grained and drusy. G4 is little altered, has some toughening and may stand out as a small cliff, e.g. on the west and east sides of Eagle Mountain ridge, or as a slight scarp, e.g. about one mile NW. of Slievemoughanmore. Well-exposed intergranite contacts also occur on the south side of Rocky Mountain (near Leitrim Lodge), and along Crotlieve and Slieve Rossley. Most contacts are sharp but an occasional gradation is found. Stages in the mechanical disruption

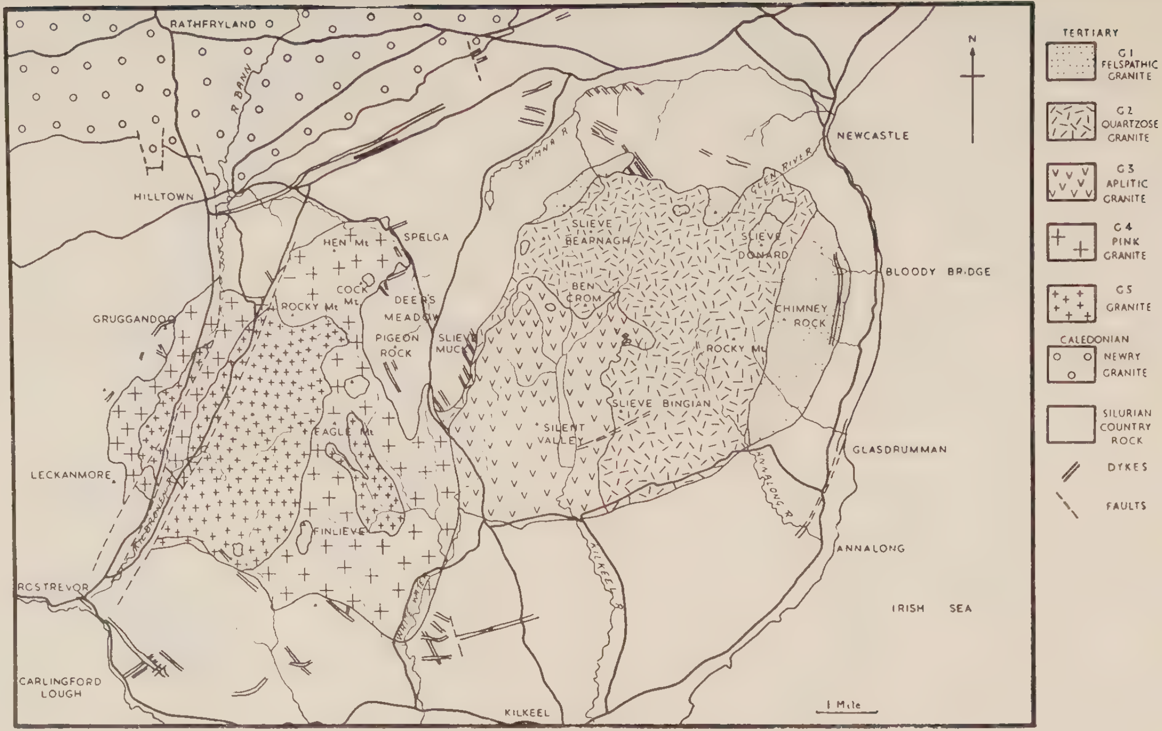

Fig. 3. Sketch-map of the Mourne Granites (after J. E. Richey and C. H. Emeleus)

of G4 by G5 may be studied on water-worn surfaces in the Kilbroney River just downstream from the road bridge three miles NNE. of Rostrevor. A similar gradation exists in the poorly exposed ground west and north-west of Finlieve.

The contacts between G4 and the Silurian rocks are sharp, the sediments being altered to tough, striped hornfelses containing biotite, diopside, plagioclase and quartz. A very narrow rim of coarsely crystalline amphibole-bearing hornfels margins the granite either side of the south spur of Pigeon Rock Mountain. Roof-like bodies of sediment appear as outliers on granite, e.g. on Slievemoughanmore; on Slievemiskan, about one mile west of Finlieve, sediments may lie directly on G5.

Acid and composite cone-sheets appear at several points about the western granites; one half mile NE. of Gruggandoo G4 cuts an acid sheet dipping SE. On the south slopes of Formal a north-dipping composite sheet has a core of porphyritic granophyre and thin dolerite margins.

Parallel faults let down a mile-wide strip of granites and sediments between Hilltown (and Leitrim Lodge) and Rostrevor; the throw increases southwards to over 1000 feet near this town.

Each granite is in roof-like relationship to the older rocks, e.g. between G4 and G5 and between G4 and the Palaeozoic rocks. These two western granites are slightly eccentric to one another, G5 being centred somewhat west of G4; thus the progressive shift of activity from ENE. to WSW., noticed in the Eastern Mournes, is continued in the Western Mournes.

Chemical data on the granites have recently become available (Brown, 1956; Emeleus, 1955; Patterson, 1953; Robbie, 1955; Taylor *et al.*, 1956), including trace elements. Gravimetric survey has revealed a gravity high coincident with these Tertiary centres, including the predominantly granitic centre of Mourne (Cook & Murphy, 1952).

Slieve Gullion, which lies some fifteen miles west of the Mournes and nine miles NW. of the Carlingford centre, rises predominantly at the centre of encircling hills and ridges which coincide with a Tertiary ring-structure (Fig. 4). The ring conforms in a remarkable way to the western margin of the older Caledonian granodiorite of Newry; Tertiary upheaval may have determined this (Bailey & McCallien, 1956). The ring is composed of two acid ring-dykes associated with basalt and trachyte lavas, vent-agglomerates and crush-breccias.

Slieve Gullion is built up of a pile of gently dipping layers, thirteen in number, which give rise to scarped and terraced slopes and consist at the base of rhyolites and basalts, including pillow lavas, and at higher levels of explosive breccias of Newry granodiorite, tuffs, granophyres and aplitic granophyres (Nos. 3, 7–9, 11–13), the whole injected by many dolerite (some gabbro) sills (Nos. 2, 4, 6, 10) and dykes. Reynolds (1951) interpreted these rocks as a faulted lava-pile now metamorphosed to

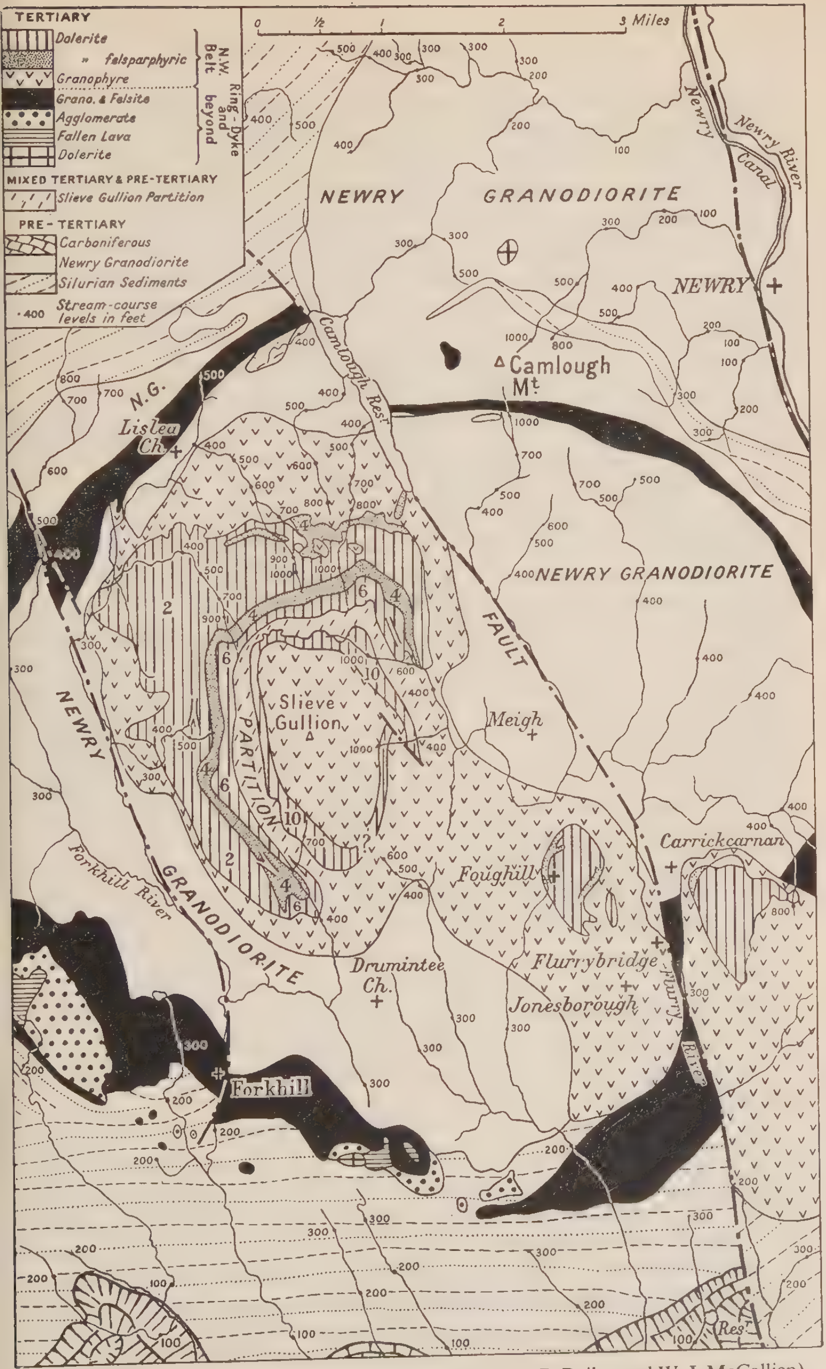

Fig. 4. Geological map of the Slieve Gullion area (after E. B. Bailey and W. J. McCallien)

medium and fine-grained rocks and preserved within a caldera defined by the ring faults and floored by Newry granodiorite. Bailey and McCallien (1956) grouped the layers into lower dolerites (2, 4, 5) 600–700 feet thick, about 800 feet of upper granophyres (3, 7–9, 11–13) and two intrusive sheets of olivine-dolerite or gabbro (6, 10), 100 and 200 feet thick. They concluded that basic magma invading relatively cool acid magma formed the 'pillow lavas'; that the basal layer (No. 1), which includes the Lislea granophyre and was thought by Reynolds to be recrystallised rhyolitic flows, was a peripheral intrusion arcuate around the NW. margin of the hill and a possible feeder of the upper granophyres.

The transgressive granophyres, derived from the Newry granodiorite, have been interpreted as a gas-transported tuff, later to be welded and recrystallised (Reynolds, 1951), or as a rheomorphic melt generated at the dolerite contacts (Bailey & McCallien, 1956). Much hinges on the interpretation of the chilled edges of the basic rocks in contact with the granophyres. Reynolds accounts for these and the associated hybrids by fusion and mixing under high temperature gas action, whilst Bailey and McCallien claim chilling of basic magma against the older acid rocks or the granophyric melt it produced. This chilling of basic against acid magma (Wager & Bailey, 1953) has been demonstrated on Slieve Gullion (Elwell, 1958).

Two major wrench-faults cross the area from the NNW. and displace the ring-dykes, especially along the Camlough–Flurry line. Many parallel minor faults cut across the ring (Richey, 1932), some of them cutting the rocks of the North-west Belt which comes north from the Carlingford area. Vertical contacts between gabbro and granophyre, however, may be intrusive or faulted; a distinction in the field is not easy to make.

The third of these plutonic centres, the Carlingford complex (Le Bas, 1960; Richey, 1932a), is emplaced in vertically folded Silurian shales and greywackes unconformably overlain by Carboniferous Limestone with basal conglomerates (Fig. 5). Following the extrusion of tholeiitic and alkaline basalt lavas, which near Rampark are 300 feet thick and dip southwards, there were intruded the Early Gabbros which form plug-like intrusions elongated NW.–SE. and show alkaline affinities; they are aligned with and similar to the Forkhill, Mullaghbawn and Cashel gabbros of the Slieve Gullion complex.

The Later Gabbros build a small lopolith, the remnants of which now cap a ring of hills (Barnavave, Slieve Foye, Carnavaddy, Doolargy, Slievenaglogh, etc.). Except for the Slieve Foye–Carnavaddy gabbros they are extensively shattered and hybridised by the underlying granophyre. At Slieve Foye, the coarse ophitic gabbros are separable into four roughly horizontal layers, each 300 feet thick. These differ little from each other and show the following characteristics: towards their bottoms, they are richer in olivine than usual, the olivine and pyroxene are more magnesian and the plagioclase more calcic; towards the tops, they are impoverished in olivine and richer in plagioclase. Cryptic and modal variations indicate fractional differentiation from a high-alumina magma. The base of the lowest layer is contaminated by the adjacent Palaeozoic rocks which are themselves altered to a pyroxene-hornfels; xenoliths of this rock are often present in the later gabbros. The gabbros of Barnavave have xenoliths of limestone with the minerals tilleyite, spurrite, idocrase, melilite, wollastonite and grossular (Nockolds, 1935, 1938, 1947, 1950).

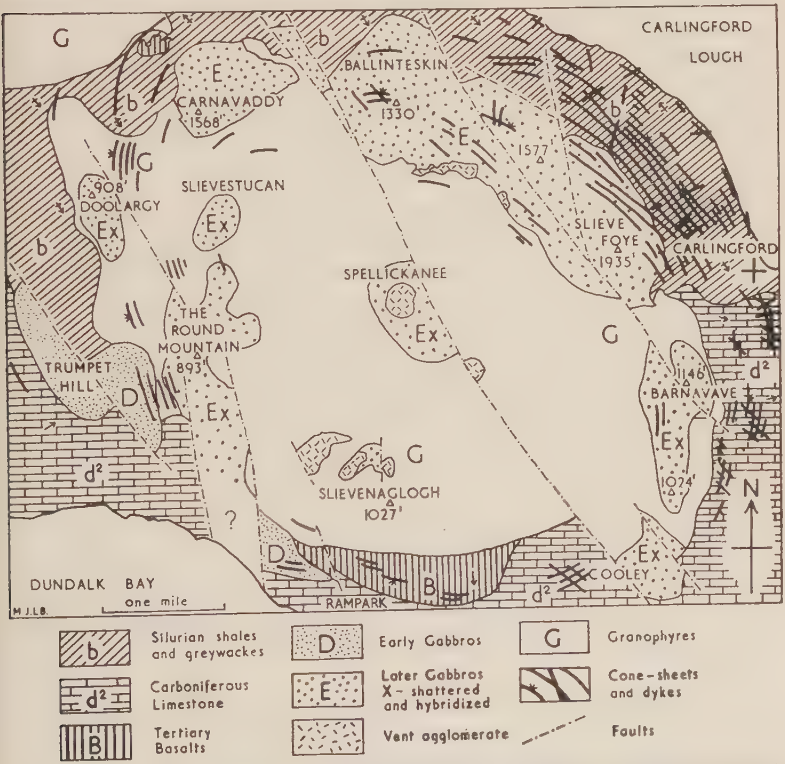

Fig. 5. Map of the Carlingford area (drawn by M. J. Le Bas from published sources)

There were two periods of granophyre intrusion separated by the injection of a series of volcanic vents; these are best exposed on Slievenaglogh, are agglomeratic and contain fragments of Silurian sediment, basalt, dolerite, gabbro and granophyre. The earlier granophyre has only been recognised as fragments in the vent agglomerates. The main granophyric body appears to belong to the later intrusion, probably a ring-dyke; near the gabbroic contacts it is hybridised. Along the limestone contacts melilite, wollastonite, diopside, forsterite, garnet, cuspidine, monticellite, phlogopite and spinel can be found. The granophyre veining the limestone is desilicated, producing a syenite containing neptunite and eudialyte.

Associated with the complex is a poorly developed set of radial dykes which vary from semi-glassy basalts to coarse dolerite. Porphyritic and non-porphyritic cone-sheets are very abundant and average five feet thick; they were injected between or during the intrusion of all the igneous rock described above. Some are olivine bearing, particularly those of pre-granophyre age. A few composite cone-sheets occur with quartz-dolerite margins and leidlitic centres.

Cutting all other rock-types is a NW.–SE. swarm of basaltic dykes; one dyke at least is rhyolitic. These and all the minor intrusions of the area are well exposed in the many limestone quarries near Carlingford.

11. POST-BASALTIC HAPPENINGS

Post-basaltic movements, both folding and faulting, followed the Tertiary igneous activity. The lavas were folded into a broad syncline centred about Lough Neagh and the Lower Bann, and faulting took place posthumously along pre-existing lines but chiefly along new directions, the beds being thrown down towards the North Channel and along the Lower Bann and along lines roughly at right angles to these, e.g. along the northern and southern sides of the Highland Border Ridge and along the Larne Water and Six Mile Water. Some of the faults which run west of north displaced the rocks outside the present limits of the flood-lavas, as in the Slieve Gullion and Carlingford areas (see Figs. 3 and 4) and, east of north, in the Western Mournes. The Tow Fault, west of Knocklayd, throws down to the west *c.* 700 feet, the Templepatrick Fault *c.* 500 feet to the south, while east of Slieve Gullion the Chalk is dropped from 1500 feet to probably about —2200 feet at Washing Bay. The age of the faulting is uncertain; it has been correlated with the Miocene or Pliocene (Eyles, 1952), a date also suggested by the fact that the Lough Neagh Clays are affected.

After the close of the igneous phase the country was subject to denudation on a considerable scale; the Mournes lost their cover, the basalts possibly a few thousand feet. Peneplains are preserved in many areas, e.g. at Deer's Meadow and at the head of the Silent Valley in the Mournes, south-east of Ballycastle, at the head of Glenarm and Glenshesk and about Slieve Gullion; Knocklayd, Slemish, Agnew's Hill, Slieve Gallion, Slieve Croob and Slieve Gullion are isolated monadnocks. The lowest plain, the counterpart of that found round the Irish Sea and the continuation of the Central Plain of Ireland, surrounds Lough Neagh, extends down the Bann and underlies the lowlands of Armagh and Down, including the Ards Peninsula. Its rivers in their upper part cut back into the higher plains in rejuvenated gorges, as in the Glens of Antrim, the tributaries of the Main and Lower Bann, the gorges about Draperstown and the gorge of the Bann above Hilltown, while in their lower parts they have gorges cut down during glacial times to more than 100 feet below present sea-level.

Sometime in this sequence of events the Lough Neagh Clays were laid down. These clays occupy the low ground which borders the southern half of Lough Neagh (see Fig. 1). Of their total area of about 200 square miles, 120 underlie the lough: the boundary for most of its length is faulted. The clays are poorly exposed so that most of the information concerning them has necessarily been obtained from boreholes. One of the most important was that at Washing Bay (Wright, 1924) which gave the maximum known thickness (1148 feet) of the Clays.

The deposits consist essentially of pale-coloured silty clays, usually blue-grey or white, with ironstone nodules and with beds of sand and lignite concentrated locally and on different horizons. Silicified wood is also present. A thick local basal conglomerate near Coalisland consists essentially of pebbles of basalt with some of Chalk, flint, sandstone and andesitic rocks set in a ground mass of decomposed basalt material (Fowler & Robbie, 1961). Pale-coloured clays occur near the surface at Ballynakelly, a few miles south-east of Coalisland, and are worked opencast for the manufacture of glazed sanitary pipes.

Although the name 'Lough Neagh Clays' was not adopted until 1912 (Cole, 1912), the existence of the clays was recorded by Griffith in 1838 who placed them in the Tertiary and compared them with the clays of Bovey Tracey in Devon. E. T. Hardman (1877) thought an immense time separated them from the outpouring of the Antrim lavas and classified them as Pliocene. Fossil plants, including *Sequoia couttsiae* and three species of *Dewalquea*, were obtained from the Washing Bay Bore (Johnson & Gilmore, 1921) and the wood of the main lignite beds was considered to belong to *Sequoia couttsiae* (Johnson & Gilmore, 1922) and indicate an Upper Oligocene age. However, specimens of *Viviparus* (*Paludina*) and *Unio* found in that bore suggest a Lower Eocene age (Wright, 1924). Subsequently *Sphagnum* was found in the clays from Washing Bay (Johnson, 1951), the genus being unknown in Europe earlier than Upper Pliocene (Harrison, 1953). This evidence agrees with J. B. Simpson's view (*in* Eyles, 1952) that the Interbasaltic Bed is of late Miocene or early Pliocene age.

Wright (1924) claimed that most of the material of the clays had been derived from a post-basaltic zone of lithomarge. Hardman, however, recognised the siliceous and aluminous nature of the deposits and deemed their main source to have been the drainage basin of the Upper Bann. Recent analyses (Fowler & Robbie, 1961) suggest that much of the clay material came from decomposed acid igneous rocks or fireclays. Much may well have been derived from the Millstone Grit, with contributions from the basalts, Chalk and Carboniferous Limestone (Fowler & Robbie, 1961).

12. GLACIAL PERIOD

During the Glacial Period this region (Charlesworth, 1939, 1953; Dwerryhouse, 1923) was overridden first by Scottish Ice from the Firth of Clyde, as is proved for example by erratics of the Ailsa Craig microgranite which occur as far west as Lough Foyle, Limavady, Dungiven, Armagh, Dromore and Newry, and later, due to the growth of Irish Ice in the west, by a confluent mass of Scottish and Irish ice which formed a diamond-shaped flow about Lough Neagh, as the dispersal of local erratics and the trend of the drumlins confirm (Fig. 6).

Following a re-advance of the ice in the south, the Carlingford Re-advance, which is delineated by a moraine well seen about the mouth of Carlingford Lough, the ice withdrew, impounding many marginal lakes to the east and west of the Lower Bann and a huge lake in the Main—the drainage was northwards—and depositing its esker gravels on the lower ground, in the valleys of the Main, Braid, Six Mile Water and Lower Bann and west of Lough Neagh. A later re-advance of Scottish ice along the Antrim coast dammed up glacier-lakes in the Lower Bann, the Glens of Antrim and the Lagan, the drainage escaping southwards from Lough Neagh by the large Pointzpass Overflow to Carlingford Lough at Newry. Local glaciers of a late phase existed about Trostan in Co. Antrim and in the Mournes.

13. POST-GLACIAL EVENTS

The Great Irish Deer (*Megaceros giganteus*), stunted shells in the marls of the White Bog, Killough, Co. Down (Stelfox, 1927), and the arctic plants in the Lower and Upper *Salix herbacea* clays (Zones I, III) prove the coldness of the late-glacial climate which was interrupted by the somewhat milder conditions (sub-arctic birch wood) of the Alleröd Period (Zone II) which is represented, for example, in the Armoy and Belfast areas (Mitchell *in* Meenan & Webb, 1957) where it followed the Antrim Coastal Re-advance. Pollen analyses of the succeeding peats show the floral and climatic changes of the country during Zones IV to IX (Jessen, 1949; Mitchell, 1951); the bog trees belong to Zone VIIb (Sub-boreal) and ceased to grow when the increasing moisture of Zone VIII (Sub-atlantic) led to the expansion of peat.

The Diatomaceous Clay (Kieselgur; Bann Clay), which extends as a thin layer along the valley of the Lower Bann between Toome Bridge and Portglenone and contains over forty species of diatoms, belongs to Zone VIIa—it has peats above (Zone VIII) and below (Zone VIc).

A low level of the sea, indicated for instance by the peat and tree layer (Zone V) in the dock sections at Belfast (Charlesworth & Erdtman, 1935),

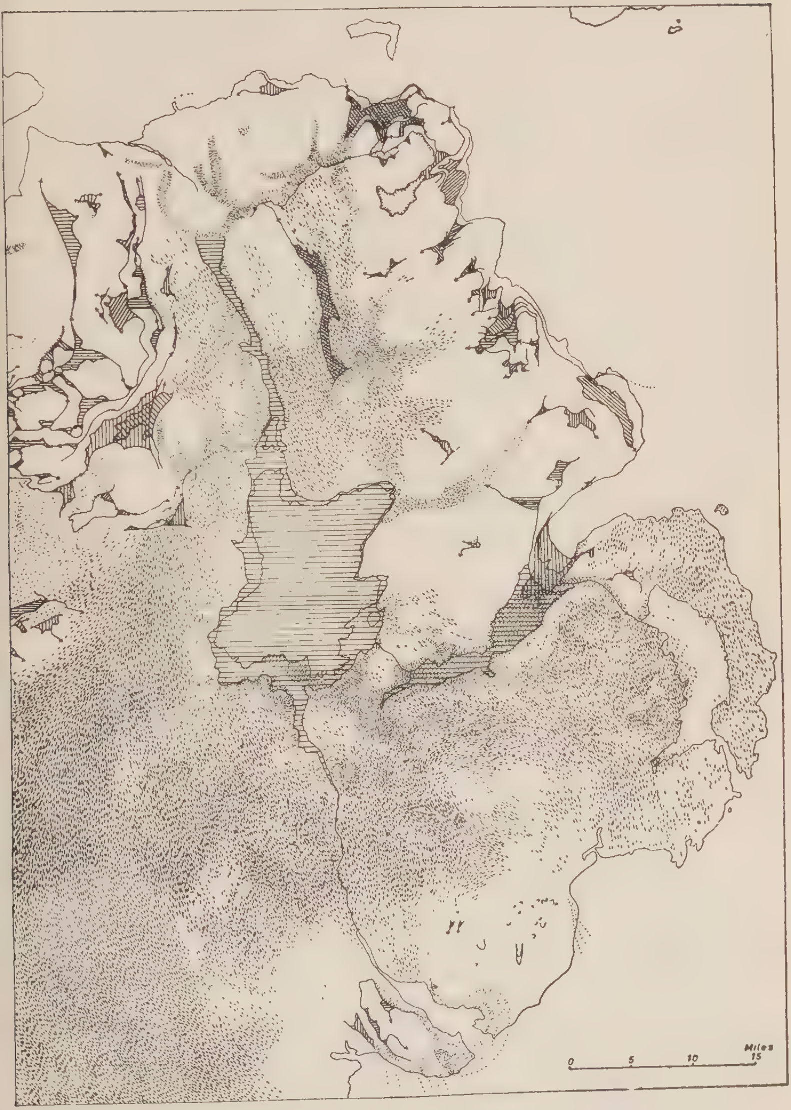

Fig. 6. Glacial map of North-East Ireland. Short strokes, drumlins; dotted areas, glacial sands and gravels; shaded areas, glacier-lakes (after J. K. Charlesworth)

was succeeded by the twenty-five foot raised beach when Estuarine Clays were laid down at the head of Strangford, Larne and Belfast Loughs—the buildings of central Belfast rest on wooden or concrete piles driven into these clays. In less sheltered places the clays are replaced by beaches (Belfast Lough, Curran of Larne, Waterfoot, Cushendun, Ballycastle, Magilligan) and on exposed coasts by rock-shelves with sea-stacks and caves (Ballycastle Harbour, Cushendun, Ballintoy Harbour, Giant's Causeway).

Early Man inhabited the region during these times; in Zone VI, Early Larnian of Larne and Cushendun (in raised beach), older Toome Bay culture; in Zone VIIa, Late Larnian; in Zone VIIb, Tievebulliagh implements, Bann culture at Newferry and Early and Middle Bronze Age. The sand-dune sites on the 'raised beaches', e.g. at Dundrum Bay near Newcastle, at White Park Bay and at the mouth of the Bann, have yielded flints and pottery of the Bronze and Iron Ages.

REFERENCES

AGRELL, S. O. & J. M. LANGLEY. 1958. The Dolerite Plug at Tievebulliagh, near Cushendall, Co. Antrim. *Proc. R. Irish Acad.*, **59B,** 93–127.

ANDERSON, F. W. 1954. *Summ. Progr. geol. Surv., Lond.* (1953), 54–6.

————. 1957. *Summ. Progr. geol. Surv., Lond.* (1956), 50–2.

BAILEY, E. B. & W. J. MCCALLIEN. 1934. The Metamorphic Rocks of North-east Antrim. *Trans. roy. Soc. Edinb.*, **58,** 163–77.

———— & ————. 1956. Composite Minor Intrusions and the Slieve Gullion Complex. *Lpool. Manchr. Geol. Journ.*, **I,** 466–501.

BROWN, P. E. 1956. The Mourne Mountains Granites. A Further Study. *Geol. Mag.*, **93,** 72–84.

CHARLESWORTH, J. K. 1937. Recent Progress in Irish Geology. *Irish Nat. J.*, **6,** 265–73.

————. 1937a. The olivine-dolerite of the Maidens, Co. Antrim. *Irish Nat. J.*, **6,** 248–50.

————. 1939. Some Observations on the Glaciation of North-East Ireland. *Proc. R. Irish Acad.*, **45B,** 255–95.

————. 1950. Recent Progress in Irish Geology. *Irish Nat. J.*, **10,** 61–71.

————. 1953. *The Geology of Ireland: An Introduction.* Edinburgh.

————. 1959. Recent Progress in Irish Geology. *Irish Nat. J.*, **13,** 49–65.

———— *et al.* 1935. The Geology of North-East Ireland. *Proc. Geol. Ass., Lond.*, **46,** 441–86.

———— & G. ERDTMAN. 1935. Postglacial Section at Milewater Dock, Belfast. *Irish Nat. J.*, **5,** 234–5.

———— & J. J. HARTLEY. 1935. The 'Tardree' and 'Hillsborough' Dyke Swarms. *Irish Nat. J.*, **5,** 193–6.

———— & A. M'I. CLELAND. 1928. 'White Trap' at Ligoniel, Belfast. *Irish Nat. J.*, **2,** 75-6.

———— & J. PRESTON. 1960. Geology around the University Towns: North-East Ireland. The Belfast Area. *Geol. Ass., Lond.* Guide 18.

CLOOS, H. 1941. Bau und Tätigkeit von Tuffschloten. Untersuchungen an dem Schwäbischen Vulkan. *Geol. Rdsch.*, **32,** 705–800.

COLE, C. A. J. *et al.* 1912. The Interbasaltic Rocks of North-East Ireland. *Mem. geol. Surv. U.K.*

———— & T. HALLISSY. 1924. *Handbook of the Geology of Ireland.* London.

COOK, A. H. & T. MURPHY. 1952. Measurements of Gravity in Ireland. Gravity Survey of Ireland north of the line Sligo–Dundalk. *Dublin Inst. Adv. Stud. Geophys. Mem.*, **2** (4).

Dawson, J. 1951. The Brockley Dolerite Plug and the Church Bay Volcanic Vent, Rathlin Island, Co. Antrim. *Irish Nat. J.*, **10,** 156–62.

Dwerryhouse, A. R. 1923. The Glaciation of North-Eastern Ireland. *Quart. J. geol. Soc. Lond.*, **79,** 352–421.

Elwell, R. W. D. 1958. Granophyre and Hybrid Pipes in a Doleritic Layer of Slieve Gullion. *J. Geol.*, **66,** 57–71.

Emeleus, C. H. 1955. The Granites of the Western Mourne Mountains, County Down. *Sci. Proc. R. Dublin Soc.* (N.S.), **27,** 35–50.

Eyles, V. A. 1952. The Composition and Origin of the Antrim Laterites and Bauxites. *Mem. geol. Surv. U.K.*

Fowler, A. 1954. *Summ. Progr. geol. Surv., Lond.* (1953), 50–53.

———. 1955. The Permian of Grange, Co. Tyrone. *Bull. geol. Surv. G.B.*, **8,** 44–53.

———. 1957. *Summ. Progr. geol. Surv., Lond.* (1956), 47–9.

———. 1958. *Summ. Progr. geol. Surv., Lond.* (1957), 44–5.

——— & J. A. Robbie. 1961. The Geology of the Country around Dungannon. *Mem. geol. Surv. U.K.*

George, T. N. 1958. Lower Carboniferous Palaeogeography of the British Isles. *Proc. Yorks. geol. (polyt.) Soc.*, **31,** 227–318.

Hancock, J. M. 1961. The Cretaceous System in Northern Ireland. *Quart. J. geol. Soc. Lond.* (in the press).

Hardman, E. T. 1877. On the Geology of the Tyrone Coal-Field and Surrounding Districts. *Mem. geol. Surv. Ireland* for Sheet 35.

Harris, N. 1936. A Petrological Study of the Portrush Sill and its Veins. *Proc. R. Irish Acad.*, **43B,** 95–134.

Harrison, J. H. 1951. Note on the history of *Sphagnum*. *Irish Nat. J.*, **10,** 153.

Hartley, J. J. 1933. Notes on Fossils recently obtained from the 'Chloritic' Conglomerate of Murlough Bay, Co. Antrim. *Irish Nat. J.*, **4,** 238–40.

———. 1936. On the Occurrence of *Saccamminopsis fusulinaformis* in Northern Ireland. *Irish Nat. J.*, **6,** 95–7.

———. 1943. Notes on the Lower Marls of the Lagan Valley. *Irish Nat. J.*, **8,** 128–32.

———. 1948. The Post-Mesozoic Succession South of Lough Neagh, Co. Antrim. *Irish Nat. J.*, **9,** 115–21.

Hull, E. 1873. On the Permian Breccias and Boulder-beds of Armagh. *Quart. J. geol. Soc. Lond.*, **29,** 402–7.

Hume, W. F. 1897. The Cretaceous Strata of County Antrim. *Quart. J. geol. Soc. Lond.*, **53,** 540–606.

Jessen, K. 1949. Studies in late Quaternary Deposits and Flora-History of Ireland. *Proc. R. Irish Acad.*, **52B,** 85–290.

Johnson, T. 1951. Fossil Plants from Washing Bay, Co. Tyrone. *Irish Nat. J.*, **10,** 150.

——— & J. G. Gilmore. 1921. The Occurrence of Dewalquea in the Coal-bore at Washing Bay. *Sci. Proc. R. Dublin Soc.* (N.S.), **16,** 323–33.

——— & ———. 1922. The Lignite of Washing Bay, Co. Tyrone. *Sci. Proc. R. Dublin Soc.*, **17,** 59–65.

Jope, E. M. 1953. Porcellanite Axes from Ireland: Tievebulliagh and Rathlin. Part I. Archaeological Survey. *Ulster J. Arch.*, **15,** 31–55.

King, W. 1853. On the Permian Fossils of Cultra. *Rep. Brit. Ass.* (1852). *Trans.* Sect. 53.

———. 1857. On the Occurrence of Permian Magnesian Limestone at Tullyconnel, near Artrea, in the County of Tyrone. *J. Geol. Soc. Dublin*, 7, 67–81.

Kirkby, J. W. 1861. On the Permian Rocks of South Yorkshire; and on their Palaeontological Relations. *Quart. J. geol. Soc. Lond.*, **17,** 287–325.

Lamplugh, G. W. *et al.* 1904. The Geology of the Country around Belfast. *Mem. geol. Surv. U.K.*

Le Bas, M. J. 1960. The Petrology of the Layered Basic Rocks of the Carlingford Complex, Co. Louth. *Trans. roy. Soc. Edinb.*, **64,** 169–200.

McCallien, W. J. 1931. A Contribution to the Correlation of the Dalradian Rocks of Scotland and Ireland. *Geol. Mag.*, **68,** 126–33.

McConnell, J. D. C. 1955. The Hydration of Larnite (B–Ca_2SiO_4) and Bredigite (Al–Ca_2SiO_4) and the Properties of the Resulting Plombierite. *Miner. Mag.*, **30,** 672–80.

M'Coy, F. 1849. On Some New Genera and Species of Palaeozoic Corals and Foraminifera. *Ann. Mag. Nat. Hist.* (2), **3,** 119–36.

McGugan, A. 1957. Upper Cretaceous Foraminifera from Northern Ireland. *J. Paleont.*, **31,** 329–48.

Meenan, J. & D. A. Webb. 1957. *A View of Ireland.* Dublin.

Mitchell, G. F. 1951. Studies in Irish Quaternary Deposits: No. 7. *Proc. R. Irish Acad.*, **53B,** 111–206.

Nockolds, S. R. 1935. Contributions to the Petrology of Barnavave, Carlingford, I.F.S. I. The Junction Hybrids. *Geol. Mag.*, **72,** 289–315.

———. 1938. Contributions to the Petrology of Barnavave, Carlingford, I.F.S. 3. On some Hybrids from the E. and SE. Slopes of Barnavave Mountain. *Geol. Mag.*, **75,** 469–79.

———. 1947. On Tilleyite and its Associated Minerals from Carlingford, Ireland. *Miner. Mag.*, **28,** 151–58.

———. 1950. On the Occurrence of Neptunite and Eudialyte in Quartz-bearing Syenites from Barnavave, Carlingford, Ireland. *Miner. Mag.*, **29,** 27–33.

——— & J. E. Richey. 1939. Replacement Veins in the Mourne Mountains Granites, N. Ireland. *Amer. J. Sci.*, **237,** 27–47.

Padget, P. 1952. Carboniferous Beds at Kildress, Co. Tyrone. *Irish Nat. J.*, **10,** 238–42.

Patterson, E. M. 1944. The Olivine-Gabbro of Ardtrea, County Tyrone. *Irish Nat. J.*, **8,** 171–76.

———. 1950. Evidence of Fissure Eruption in the Tertiary Lava Plateau of North-East Ireland. *Geol. Mag.*, **87,** 45–52.

———. 1951. An Occurrence of Quartz-Trachyte among the Tertiary Basalt Lavas of North-East Ireland. *Proc. R. Irish Acad.*, **53B,** 265–87.

———. 1953. Petrochemical Data for some Acid Intrusive Rocks from the Mourne Mountains and Slieve Gullion. *Proc. R. Irish Acad.*, **55B,** 171–88.

———. 1955. The Tertiary Lava Succession in the Northern Part of the Antrim Plateau. *Proc. R. Irish Acad.*, **57B,** 79–122.

———. 1955a. The Tertiary Volcanic Succession in the Western Part of the Antrim Plateau. *Proc. R. Irish Acad.*, **57B,** 155–78.

——— & D. J. Swaine. 1957. The Tertiary Dolerite Plugs of North-East Ireland, etc. *Trans. roy. Soc. Edinb.*, **63,** 317–31.

Portlock, J. E. 1843. *Report on the Geology of the County of Londonderry and of parts of Tyrone and Fermanagh.* Dublin.

Pugh, W. J. 1958. *Summ. Progr. geol. Surv., Lond.* (1957), 5–21.

Reid, R. E. H. 1958. Remarks on the Upper Cretaceous Hexactinellidae of Co. Antrim. *Irish Nat. J.*, **12,** 236–43, 261–8.

———. 1959. Age of the Cretaceous Basal Conglomerate at Murlough Bay, Co. Antrim. *Geol. Mag.*, **96,** 86–7.

Reynolds, D. L. 1928. Petrography of the Triassic Sandstone of North-East Ireland. *Geol. Mag.*, **65,** 448–73.

———. 1931. The Dykes of the Ards Peninsula, Co. Down. *Geol. Mag.*, **68,** 97–111, 145–65.

———. 1934. The Eastern End of the Newry Igneous Complex. *Quart. J. geol. Soc. Lond.*, **90,** 585–636.

———. 1940. Contact Metamorphism by a Tertiary Dyke at Waterfoot, Co. Antrim. *Geol. Mag.*, **77,** 461–9.

———. 1942. The Albite-Schists of Antrim and their Petrogenetic Relationship to Caledonian Orogenesis. *Proc. R. Irish Acad.*, **48B,** 43–66.

———. 1943. The South-western End of the Newry Igneous Complex. A Contribution towards the Petrogenesis of the Granodiorites. *Quart. J. geol. Soc. Lond.*, **99,** 205–46.

———. 1951. The Geology of Slieve Gullion, Foughill, and Carrickcarnon; an actualistic interpretation of a Tertiary gabbro-granophyre complex. *Trans. roy. Soc. Edinb.*, **62,** 85–142.

Richey, J. E. 1927. The Structural Relations of the Mourne Granites. *Quart. J. geol. Soc. Lond.*, **83,** 652–88.

RICHEY, J. E. 1932. The Tertiary Ring-complex of Slieve Gullion. *Quart. J. geol. Soc. Lond.*, **88,** 776–849.

———. 1932a. Tertiary Ring Structures in Britain. *Trans. geol. Soc. Glasg.*, **19,** 42–140.

ROBBIE, J. A. 1955. The Slieve Binnian Tunnel, An Aqueduct in the Mourne Mountains. *Bull. geol. Surv. G.B.*, **8,** 1–18.

———. 1955a. The Carboniferous Rocks of Edendork, Co. Tyrone. *Bull. geol. Surv. G.B.*, **8,** 21–37.

——— & H. E. WILSON. The Geology of the Country around Ballycastle. *Mem. geol. Surv. U.K.* (in preparation).

STELFOX, A. W. 1927. An Arctic Peat in Ireland. *Nature*, **119,** 781.

TATE, R. 1865. On the Correlation of the Cretaceous Formations of the North-east of Ireland. *Quart. J. geol. Soc. Lond.*, **21,** 15–44.

TAYLOR, S. R., C. H. EMELEUS & C. S. EXLEY. 1956. Some Anomalous K/Rb Ratios in Igneous Rocks and their Petrological Significance. *Geochim. et cosmoch. Acta*, **10,** 224–9.

TILLEY, C. E. & H. F. HARWOOD. 1931. The Dolerite-Chalk Contact of Scawt Hill, Co. Antrim. The Production of Basic Alkali-rocks by the Assimilation of Limestone by Basaltic Magma. *Miner. Mag.*, **22,** 439–68.

TOMKEIEFF, S. I. 1934. Differentiation in Basalt Lava, Island Magee, Co. Antrim. *Geol. Mag.*, **71,** 501–12.

———. 1940. The Basalt Lavas of the Giant's Causeway, etc. *Bull. volcan.* (2), **6,** 89–143.

———. 1940a. The Dolerite Plugs of Tieveragh and Tievebulliagh near Cushendall, Co. Antrim, with a Note on Buchite. *Geol. Mag.*, **77,** 54–64.

——— & C. E. MARSHALL. 1935. The Mourne Dyke Swarm. *Quart. J. geol. Soc. Lond.*, **91,** 251–92.

——— & ———. 1940. The Killough–Ardglass Dyke Swarm. *Quart. J. geol. Soc. Lond.*, **96,** 321–38.

——— & E. M. PATTERSON. 1947. The Tertiary Igneous Rocks in the Neighbourhood of Ballintoy, Co. Antrim. Part I. The Knocksoghey Sill. *Irish Nat. J.*, **9,** 89–96.

——— & ———. 1948. The Tertiary Igneous Rocks in the Neighbourhood of Ballintoy, Co. Antrim. Part II. The Carrickarade Volcano. *Irish Nat. J.*, **9,** 203–12.

——— & ———. 1953. The Tertiary Igneous Rocks in the Neighbourhood of Ballintoy, Co. Antrim. Part III. The Coast near Ballintoy Harbour. *Irish Nat. J.*, **11,** 35–45.

VERSEY, H. C. 1958. Derived Ammonites in Basal Cretaceous Conglomerate. *Geol. Mag.*, **95,** 440.

WAGER, L. R. & E. B. BAILEY. 1953. Basic Magma chilled against Acid Magma. *Nature*, **172,** 68–9.

WALKER, G. P. L. 1948. A Preliminary Note on the Metamorphic Rocks of the Portmuck Area, Islandmagee, Co. Antrim. *Irish Nat. J.*, **9,** 165–8.

———. 1951. The Amygdale Minerals in the Tertiary Lavas of Ireland. I. The Distribution of Chabazite Habits and Zeolites in the Garron Plateau Area, County Antrim. *Miner. Mag.*, **29,** 773–91.

———. 1959. Some Observations on the Antrim Basalts and Associated Dolerite Intrusions. *Proc. Geol. Ass., Lond.*, **70,** 179–205.

———. 1960. An Occurrence of Mugearite in Antrim. *Geol. Mag.*, **97,** 62–4.

WHITE, W. C. & E. M. PATTERSON. 1949. Kaolinisation in the Granite of the Mourne Mountains. *Irish Nat. J.*, **9,** 298–301.

WILSON, H. E. 1953. The Petrography of the Old Red Sandstone Rocks of the North of Ireland. *Proc. R. Irish Acad.*, **55B,** 283–320.

WRIGHT, W. B. 1924. Age and Origin of the Lough Neagh Clays. *Quart. J. geol. Soc. Lond.*, **80,** 468–88.

———. 1924a. The Geology of the Ballycastle Coalfield. *Mem. geol. Surv. U.K.*

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